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HUGO, BARON HIRST, OF WITTON.

November 26th, 1863.

January 22nd, 1943.

Lord Hirst, of Witton.

THE twenty-second of January, 1943, was a sad day in the annals of The G.E.C., for on that day died our Founder and Chairman, Lord Hirst, of Witton. Yet it was some mitigation of our sorrow to reflect that death only took Lord Hirst at the end of a long life during which he had seen the realisation of his ambitions, the fulfilment of his dreams, and the great organisation which he had created functioning smoothly and with its wonted efficiency in the hands of those younger men whom he himself had selected and trained.

Lord Hirst was born in Munich in 1863, and at the age of 16 migrated to this country which he was to make his home.

A few years later, in 1886, he joined Mr. G. Byng, our first Chairman, in The General Electric Apparatus Company, which was a small "electrical shop" in Great St. Thomas Apostle.

So great and so rapid has been the development of the electrical industry that it is difficult for us to picture what it was like in the 'eighties of last century. The telephone had been invented in 1878 and the same year had seen the so-called sub-division of the electric light by the invention simultaneously by Edison in America and Swan in this country, of the carbon filament lamp. The exploitation of these two inventions was only just started and this country had been late in starting owing to unwise legislation which was not corrected until 1888. Consequently, in this country, the commercial use of electricity was largely confined to big users such as the railways and the like who were able to generate their own supply. No sort of standardisation had been effected but, on the contrary, each engineer was accustomed to design his own accessories. In these conditions it required no little courage and vision to embark on a business of supplying such accessories. That courage and vision Hirst possessed then and has possessed throughout his long career. It did not take long to demonstrate the accuracy of his judgment for in 1889 the Company had to be enlarged and the opportunity was taken to change the name to The General Electric Company.

Very early in his efforts to build up the business Hirst realised that he must not be content to act as a middleman between the maker and the user but must also be prepared to make on his own account, and it was not long before the question of manufacturing on a really big scale (for those days) posed itself. Given a man of Hirst's temperament and outlook there could be only one answer to this question but it required some persuasion to get the consent of the more cautious Mr. Byng to such an expansion of their activities. That consent obtained, a factory was bought in Manchester in 1888 and the G.E.C. began its manufacturing career on a small scale. This was expanded in 1893, and in this year the Peel Works, Salford, was started.

Peel Works was devoted in its early years to the miscellaneous manufacture of the various accessories used in electric lighting and bell and telephone work and hardly deserved the name of being a definite industry, but opportunity was not to be long delayed and Hirst conceived the idea that when the Edison and Swan master patents expired there would be room for an independent manufacturer of electric lamps. This was a highly technical manufacture and Hirst looked for an expert with the necessary knowledge and found him in the person of Mr. Robertson who had gained his experience abroad and with whom Hirst started the Robertson Works at Hammersmith in 1895. Hirst made his preparations in ample time and when the patents actually expired he was ready with the Hammersmith products to supply the market.

The next step was an even bolder venture; the creation of the Witton Works. This was in 1901. Witton was conceived by Hirst as being destined to house the whole manufacturing efforts of the G.E.C., but he later abandoned this idea in favour of spreading the enterprises throughout the country, choosing for each the most suitable site where the right sort of labour was obtainable and other conditions were satisfactory.

Witton was constructed for undertaking the heavy side of electrical engineering; the manufacture of generators and motors and such manufacture of these as was already being done at Peel Works was transferred here. But Witton was also the site of another enterprise which displays in a still more convincing fashion the far-seeing vision and the dauntless tenacity of our Chief. This was the Carbon Works put up for the manufacture of arc lamp carbons.

Hirst thus introduced into this country an industry which was of vital importance, for, up till then, the Admiralty and the War Office

had been dependent on imported carbons for their searchlights. The importers put up a strong fight to make the Carbon Works a failure but Hirst was not daunted by the loss on the enterprise, which amounted to £70,000 in the first ten years and the reward of his courage came with the outbreak of War in 1914 when the works had to be speedily doubled and were the mainstay not only of our own war machine but also of some of our Allies.

It is not necessary to tell of the other enterprises in detail but mention may be made of the Telephone Works at Coventry, the Cable Works at Southampton and the Engineering Works at Erith, all of which, with other lesser factories, completed in due course the framework of the G.E.C. as manufacturers of all electrical products.

Hirst was no mere copier but was always determined to pioneer, and with this object in view he established the Research Laboratories shortly after the Great War. These are now acknowledged to be among the finest industrial laboratories in the world.

Whether on the selling side or in the various factories Hirst from the beginning insisted on the need to foster the community spirit and the fine club buildings which exist in all the major G.E.C. Works bear ample testimony to this. Another evidence of his anxiety to care for those who served the G.E.C. is to be found in the Pension Fund which he established and which now has accumulated funds of over two million pounds.

The knowledge, the experience and the wisdom gained in the building of the G.E.C. Organisation were always at the service of the country and as Hirst proved by the success of his enterprise the soundness of his judgment, outside bodies and the Government came more and more to him for help and advice.

In this way he served on the Federation of British Industries, of which he was President in 1937. He was also on the Institute of Fuel and was one of the very few honorary members of the Institution of Electrical Engineers. From his earliest years he was a keen believer in Tariff Reform and when this country adopted a protectionist policy after the Great War he was frequently consulted by the Government in framing the details of that policy. In addition he served on the Board of Trade Advisory Council and was Economic Adviser to the Cabinet Research Committee and a member of the Cabinet Trade and Employment Panel. He was invited by the Government to be one of the four business experts to visit Australia in 1928 with the object of conferring with leaders of industry there and with the Government of the Commonwealth on the best method of developing Australia's resources.

With all these activities he nevertheless found time to indulge his fondness for sport and kept a small racing stable and his horse Diolite was favourite for the Derby in 1930, but actually finished only third.

We have given in the above account the tale of Lord Hirst's life as it shows, by what he accomplished, the type of man we have lost. He needs no other monument than the G.E.C. with its 50,000 employees, but an attempt must be made to describe the man who constructed this great organisation and to do this we can not do better than quote an appreciation which the present writer made when Lord Hirst was raised to the peerage:

"He possesses in a supreme degree the essential qualities of leadership; a broad, far-seeing outlook at once imaginative and creative; the courage and the perseverance that achieve success in their objective unperturbed by the difficulties of the road; a grasp of essentials that finds a way through the wood despite the multitude of trees; and, above all, a personality and an honesty of purpose that inspire trust and confidence in those whose privilege it is to follow his lead. . . . . ."

"The task which he set himself at the beginning of his career—to build in the British Empire an electrical industry second to no other in the world—Lord Hirst has successfully achieved. It was a task which would have been far easier had the early conditions not been so unfavourable. Social and legislative conditions in this country added immensely to the difficulty and the knowledge that Great Britain was a late starter in the race and had to catch up its more favoured foreign competitors would have discouraged a less far-seeing man. This only added to Lord Hirst's determination, and the will to succeed, fortified by the conviction that success was obtainable if the effort was made, carried him over all obstacles. To-day he can look round with content on a British electrical industry which can acknowledge equals in a few other countries, but need bow before no superior, and he can see, with pride, the G.E.C. the leading organisation in that industry."

Lord Hirst married in 1892 and had one son and two daughters. Lady Hirst died in 1938. His son died as a result of the Great War in 1919, leaving a grandson, who was killed on operational duties with the R.A.F. in 1941; therefore the peerage becomes extinct. His elder daughter is now the Hon. Mrs. Gamage, being married to our present Vice-Chairman and Joint Managing Director, and his younger daughter is the Hon. Mrs. Trevor Rose, the wife of Group Captain Trevor Rose.

Lord Hirst was created a Baronet in 1925 and a Baron in 1934.

M.S.

Refractory Materials for Glass Making.

By J. H. PARTRIDGE, B.Sc., Ph.D., F.S.G.T.,
G.E.C. Research Laboratories.

INTRODUCTION.

GLASS is melted in containers built of fireclay blocks. This fireclay is slowly dissolved by the molten glass and so the life of the containers is affected by its quality, particularly at the high temperatures at which it is used. The solution of these fireclay blocks in molten glass is responsible as a rule for the ultimate shutting down of the glass melting furnace and so is of interest to glass makers. Differences between fireclay blocks which have given satisfactory and unsatisfactory service in glass tank furnaces are described in this article.

Very brief accounts of the composition of glass and of the development of the art of glass making are given in order to make the subject more easily understood by readers to whom it may not be familiar.

COMPOSITION OF GLASS.

Glass is probably the oldest of artificial materials and was being made nearly 8,000 years ago. The oldest piece of glass bearing a date is of Egyptian manufacture, but glass of this period (XVIII Dynasty c.1580 to 1320 B.C.) is plentiful, and, indeed, coloured glass amulets were worn at least 2,000 years earlier. There is evidence that this glass was exported from Syria and that the art of glass making was introduced into Egypt from there.

Sodium silicate, made by heating a mixture of sand and soda, is one of the simplest kinds of glass; the legend* that it was accidentally made by Phoenician merchants gives a possible explanation of the discovery of glass making, because simple soda-silica glass can be made at temperatures attainable in a wood fire burning in the open. Such soda-silica glass is soluble in water—hence the term water glass—so that other oxides have to be added to render it more resistant to solution and to attack by weathering agencies. In this connection it is interesting to note that Pliny records the conversion of sodium silicate to a more permanent glass by the addition of lime and magnesia, and that these oxides are still used for this purpose.

Thus it will be appreciated that glass consists essentially of a glass-forming oxide—usually silica—fluxes or alkalis, and stabilising oxides such as lime, magnesia or lead oxide. Silica is the outstanding glass-forming oxide because silica glass† possesses in the highest

Fig. 1. Glass making in the 16th century from Georg Agricola's "De Re Metallica," published in 1556.

* The tradition, according to Pliny, assigns the discovery to Phoenician merchants:—"Finding no stones at hand for supporting their cauldrons, they employed for the purpose some lumps of nitre which they had taken from the vessel. Upon its being subjected to the action of the fire, in combination with the sand of the sea shore, they beheld a transparent stream flowing forth of a liquid hitherto unknown; that, it is said, was the origin of glass." "Properties of Glass"—GEORGE W. MOREY, Reinhold Publishing Corporation, New York.

† Commonly, though erroneously, called "fused quartz."

TABLE I.

Percentage Chemical Composition of Glass for various uses compared with Ancient Glass.

	Ancient Egyptian	Bottle	Window	Plate	Common pressed glass	Electric lamp and valve bulbs	English crystal glass	"Resistance" glass for electrical purposes	Heat resisting glass
Silica	63	73	70.5—72	72—73	72—74	71.5—73.5	52—55	56—57	75—80
Soda	21	16	15—17	12—13	17—18	16—17	—	5—6	3—5
Potash	1	—	—	—	—	—	11—13	7—8	0.5—2
Lime	9	8—9	9—11	13—15	6—8	5—6	—	—	0—3
Magnesia ..	5	0—3	0—3	—	0—3	3.5—4.5	—	—	—
Alumina ..	1	0.5	0.8—1.5	0.5—1.5	1—2	1—2	—	0.5—1.0	1—3
Lead Oxide ..	—	—	—	—	—	—	31—35	28—31	—
Boric Oxide ..	—	—	—	—	—	—	—	—	10—15

degree many desirable properties such as resistance to sudden changes in temperature and to attack by water and chemical reagents. If it were not so difficult to melt, silica glass would be a very suitable material for most of the uses to which glass is put. The difficulty and cost of manufacture prohibit its use for general purposes, so other oxides have to be employed to combine with, or flux, the silica and so lower its melting point and reduce its viscosity. The most effective flux is soda, an addition of 25 per cent lowering the melting point from 1710 degs. to 793 degs. C. This is the eutectic mixture and large quantities of glass of this composition are made annually in the soluble silicate industry. The oxides normally added to confer chemical durability and so produce a stable glass are lime and magnesia, because they are efficacious, cheap and readily available in a pure state. If too little lime is added, the glass is not highly resistant to weathering, although it is easy to melt. From this point of view much of the ancient glass would be rejected to-day because of its high soda content, and it is questionable whether it would have survived but for the dry climate of Egypt. Increasing the proportion of silica improves the chemical and thermal durability and produces the well known heat resisting glasses of low thermal expansion, but these are more difficult to make than the less viscous, "softer" glasses containing higher proportions of alkali. The greatest tonnage of glass melted to-day is of the soda-lime-silica type, the chemical composition lying between the limits :

Silica	73—74	per cent.
Sodium Oxide ..	13—18	„ „
Lime	7—12	„ „
Magnesia	0—4	„ „

Glass within this range of composition is used for bottles, food containers, sheet and plate glass, electric lamp and radio valve bulbs, to mention just a few of its applications. Smaller proportions of other oxides are added either to confer greater stability or to attain specific properties ; the compositions of typical glasses together with their uses are given in Table I.

BRIEF ACCOUNT OF GLASS MAKING.

Glass when first made was coloured ; it was precious and was used solely for gems. Later, glass vessels were made by moulding round a sand core supported on a wooden or iron rod. The sand core was covered bit by bit with viscous glass at a temperature not much above its softening point, and, on removing the sand, a hollow vessel was obtained. This building-up process needed a "soft" glass—hence the low silica and high alkali content of the ancient Egyptian glass to which reference has already been made. The invention of glass blowing* just before the beginning of the Christian era, coupled with the stability of the Roman Empire, caused a rapid expansion of the industry and glass makers were so numerous in Rome that a portion of the city was assigned to them.

Little information is available about glass during the period from the fall of the Roman Empire to the 11th century when glass making

* In blowing, the bulbous end of an iron tube, some 40 inches in length and ¾ inches in diameter, is rotated just beneath the surface of the molten glass ; on withdrawal, a portion of viscous glass remains attached to it. If the workman now blows into the mouthpiece end of the iron tube or blowing iron, he forms a hollow bulb in the pendent mass of viscous glass. The bulb grows larger and the wall becomes thinner as more air is blown in. Its shape is controlled by the manipulative skill of the blower—for example the bulb can be lengthened into a tube by careful swinging of the blowing iron. The external form is frequently controlled by the bulb being finally blown to shape in a mould.

in Venice entered a period of development, and for the next 400 years Venice was the centre of a large industry which attained the highest skill and was jealously protected. Religious persecution in the 16th century resulted in foreign glass workers settling in England, and there were applications for monopolies for glass making, the applicant usually undertaking to make glassware as good and as cheap as that then imported from Venice, to bring foreign workmen into this country, and to teach the art to Englishmen. These early glass makers consumed large quantities of wood, not only to heat their furnaces but also to provide crude alkali for glass making, and protests were soon made in Parliament that the countryside was being devastated by them. That these protests were effective is shown by the fact that the use of wood for fuel was forbidden four years after the granting of a patent in 1611 for the burning of coal in glass making furnaces.

Glass making in the 14th and 15th centuries was conducted as follows :—beechwood or brake fern was calcined for its ash, which was collected, dissolved in water and precipitated to

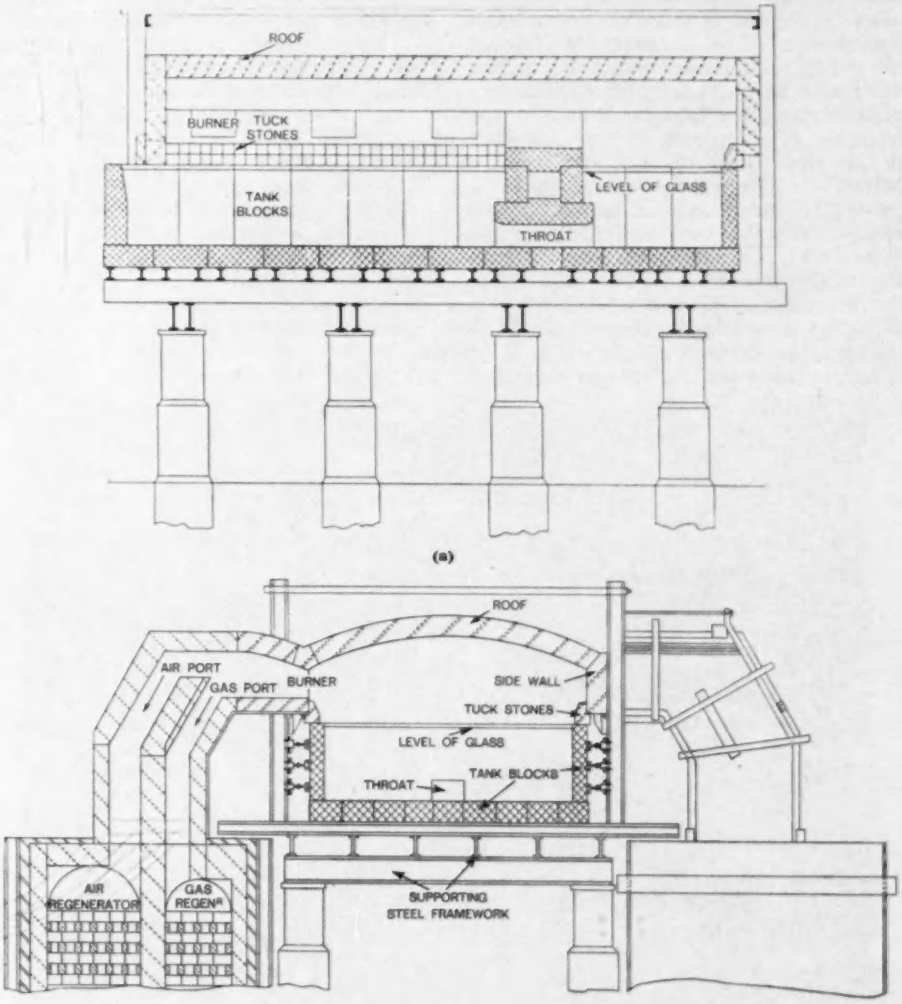


Fig. 2 (a) **Longitudinal section of a typical glass tank furnace.**
(b) **Cross-section of the glass tank furnace.**

provide the crude alkali known as pearl ash, now called potash. The mixture of sand, lime and pearl ash was partially fused to a frit in the "calcar" furnace. When cool, the frit was broken into lumps and shovelled into fireclay melting crucibles. As the formation of glass proceeded, the impurities in the chemicals rose to the surface forming a crust which was removed by skimming. The glass was then ladled into water, dried and re-melted. In spite of this purifying and second melting treatment, the glass was of inferior quality. The illustration in fig. 1 taken from Agricola's "De Re Metallica," published in 1556, gives an idea of the methods employed in glass making in the 16th century. Melting in larger crucibles at higher temperatures and the use of purer chemicals effected an improvement but, apart from these innovations, the process of glass making changed little until the latter part of the 19th century when the development of automatic machines for making sheet glass and bottles created a demand for larger masses of molten glass. This was met by melting in tank furnaces instead of in pots.

The general construction of a glass tank furnace is explained by the drawings in fig. 2 and the photograph of an interior in fig. 3. It is a large rectangular furnace containing a bath of molten glass some 10 to 20 feet in width, 20 to 40 or more feet in length and between 3 and 4 feet in depth; the dead-weight capacity of such furnaces varies from about 100 to over 500 tons of glass. The bath containing the pool of molten glass is built of fireclay tank blocks 8 to 15 inches in thickness; the upper walls and crown of the furnace are supported separately from the fireclay bath so that they do not have to be disturbed when the fireclay blocks are renewed. The joint between the upper walls and tank blocks is closed by means of tuck stones. The glass is kept hot by the combustion of producer gas and air issuing from the ports along one side of the furnace, and the products of combustion leave by the ports on the other side. In order to attain the high temperature needed for glass making, the gas and air are pre-heated in the regenerators in the usual manner. Raw materials, consisting principally of sand, lime and sodium carbonate, are charged in one end of the furnace, they re-act at the high temperature to form glass which slowly flows to the working end of the tank. In doing so it has to flow through a hole, or throat, in a double walled bridge which divides the melting end from the working end. The blocks forming the side walls and throat are often attacked so severely by the molten

Fig. 3. Interior of a glass tank furnace newly lined and before being put into operation. Note the new tank blocks (D), tuck stones (B), throat (A), side wall (C), and compare with fig. 4 which shows the same furnace at the end of its useful life.

glass that the tank furnace has to be shut down for extensive repairs after, roughly, 12 months' service.

It was soon found that the industry had been transformed from one dependent on the manipulative skill of the glass blower who is able to adjust the speed of his movements to deal with slight variations in the viscosity of his glass, to one dominated by the machine requiring closely controlled conditions of glass composition and temperature. To achieve this close control, the furnace must be operated under as steady conditions of temperature and output of glass as possible because :

(i) the viscosity of glass changes very rapidly with temperature.

(ii) fluctuations in temperature alter the rate of loss of alkali by volatilisation from the surface of the molten glass and so give rise to streams of glass of different composition within the tank ; this results in "streaky" or "cordy" glass.

(iii) fluctuations in output also result in cordiness because more or less stagnant glass is drawn into the current of molten glass flowing to the machines.

Variables (ii) and (iii) can be minimised by careful control of operating conditions, but there is another factor affecting production of glass of uniform quality which is scarcely within the scope of furnace operation. It is the inevitable solution of the fireclay lining of the tank in molten glass.

Molten glass is corrosive and the extent of its attack on the refractories is apparent by comparing figs. 3 and 4, which are photographs of the interior of a glass tank furnace taken at the beginning and end of its useful life. The thickness of the blocks at the glass level has been reduced from 8 inches to less than 1 inch in the hottest parts of the furnace, and a large proportion of the throat cover block has been eaten away. The quantity of tank block material taken into solution is thus considerable, and this solution of refractory material results firstly in the ultimate shutting-down of the furnace for repairs, with consequent loss in production, and secondly in a deterioration of the quality of the glass. The glass becomes cordy because it contain threads of glass of different temperature-viscosity characteristics owing to the solution of refractory material. Lowering the temperature of operation decreases the speed of this chemical attack, but in general this course cannot be taken. The only practical manner in which better performance of glass tank furnaces can be achieved lies in

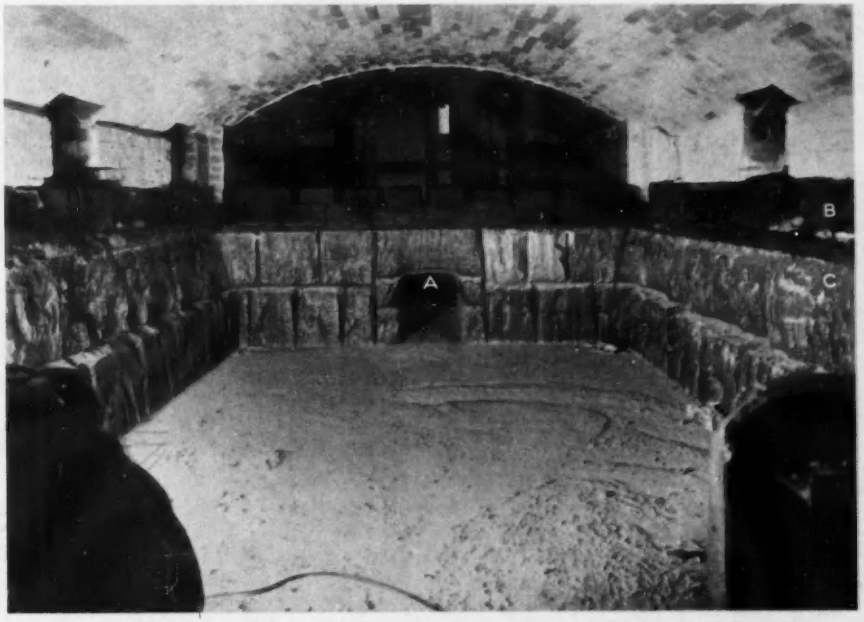
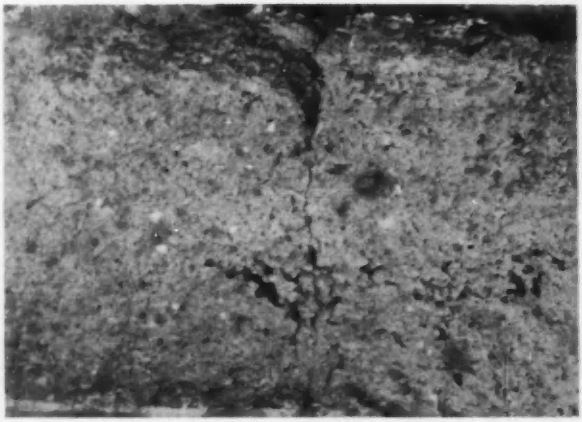


Fig. 4. Interior of a glass tank furnace at the end of its melting campaign, after the glass has been drained out. Note the throat cover block worn away (A) and the wear of tuck stones (B) and side wall tank blocks (C).



non-plastic particles, the quality of the bond clay and the efficacy of the firing treatment given by the manufacturers. It can be shown that a well fired block possessing a close, dense texture is more resistant to corrosion than a block with a loosely bonded open texture (compare figs. 5 and 6). An estimate of the texture and porosity is easily made, but that of firing treatment is more difficult and is best determined from the X-ray spectra. Differences between qualities of blocks are revealed by their X-ray spectra, and especially by changes in their crystalline constituents which take place when specimens are refired in the laboratory.

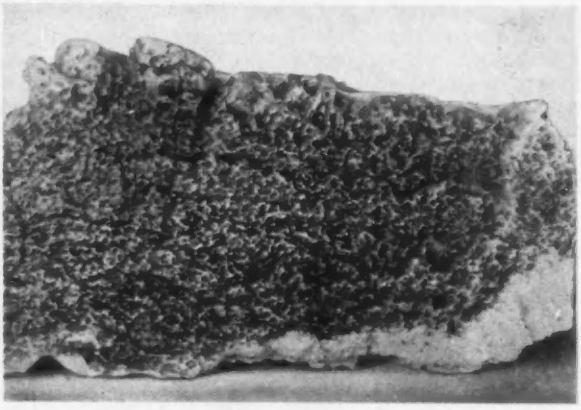


Fig. 5 (above). **Texture of tank block which gave poor service, showing open, porous texture with loosely bonded particles of grog (approximately full size).**

(right). **Working face of the block illustrated above showing severe corrosion and pitting of the surface. Note small fragments of block almost severed from main body. When completely severed they float away in the molten glass, forming either "stones" or "cord" in the finished ware (approximately full size).**

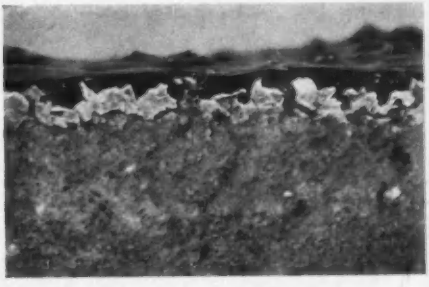
(below). **Section through glass refractory interface of the tank block showing particles of refractory almost detached from main body (approximately full size).**

the use of blocks possessing increased resistance to solution. From several points of view, therefore, the assessment of the quality of tank blocks by laboratory tests is highly desirable.

THE CONSTITUTION OF TANK BLOCKS.

Tank blocks are made either of fireclay or of sillimanite; both types consist of a large proportion of non-plastic particles, generally between 60 and 80 per cent, to which clay is added to confer the plasticity needed for moulding to shape. The non-plastic particles are grains of burnt fireclay in fireclay blocks and of calcined kyanite in sillimanite blocks. After being moulded and allowed to dry very slowly, the tank blocks are fired to a high temperature by the makers before being delivered to the glass works.

Thus it is evident that tank blocks possess a texture defined by the size and grading of the



Fireclay Blocks.

Briefly, good quality fireclay consists of a plastic aluminium silicate, or clay substance, associated with non-plastic free silica and accessory minerals such as micas and felspars. On being fired the clay substance first breaks down at about 550 degs. C. and later re-

combines to form mullite and silica. The reaction may be represented :

$$Al_2O_3.2SiO_2.2H_2O \rightarrow 3Al_2O_3.2SiO_2 + SiO_2 + H_2O$$

Clay substance → mullite + silica + water vapour.

The crystals of mullite begin to form at a temperature of about 1050 degs. C. and increase in size as the temperature is raised. A properly fired clay block thus contains well developed crystals of mullite, in contrast with the poorly developed crystals in under-fired material. Further, in well fired material little or no change in the state of crystallisation of the mullite is observed between the material in the "as received" and "refired" conditions.

In the original clay, the free silica is present in the low-temperature form α quartz, but this is converted to the high temperature forms, tridymite and cristobalite, when clay is properly fired. The presence therefore of α quartz in tank block material indicates that it has not been fired to a sufficiently high temperature. In Table II, B and C are examples of under-fired clay blocks, and the changes in their constitution brought about by the refiring treatment should be noted ; their structures should also be contrasted with that of the well fired block A. Block C was taken from the throat cover block shown in fig. 4 which gave poor service ; X-ray examination showed that this block could not have been fired at a temperature higher than 1250—1300 degs. C., whereas the suppliers were of the opinion that they were firing to at least 1400 degs. C. Block A gave good service in the glass melting furnace.

Absence of α quartz is not in itself proof that the firing treatment of the tank block has been adequate. The state of crystallisation of the mullite is a more reliable indication, particularly as well developed mullite crystals are not generally formed below about 1400 degs. C. For example block D in Table II contained little or no quartz, but the changes which took place when the block was refired indicated initial underfiring. The pronounced fall in the value of the porosity on refiring also indicates a badly fired block.

"Sillimanite" Blocks.

The term "sillimanite" is usually a misnomer because blocks neither contain sillimanite nor have they been made from the mineral sillimanite. So-called "sillimanite" refractories are usually made from calcined kyanite,* which, after calcining, consists of mullite and cristobalite, frequently associated with corundum and with a siliceous glassy phase, provided the calcination is carried out at temperatures in excess of 1300 degs. C.

The reaction during calcination may be represented :

$$Al_2O_3.SiO_2. \rightarrow 3Al_2O_3.2SiO_2 + SiO_2$$

Kyanite → mullite + silica

Calcined kyanite is non-plastic and so is mixed with a minor proportion of plastic bond clay for moulding.

As in clay blocks, the condition of growth of the mullite crystals gives the best indication of the firing treatment. From this point of view, block F in Table II has not been well fired compared with block E because growth of mullite crystals took place when it was refired, whereas no change occurred in the constitution of block E. Block F happens to

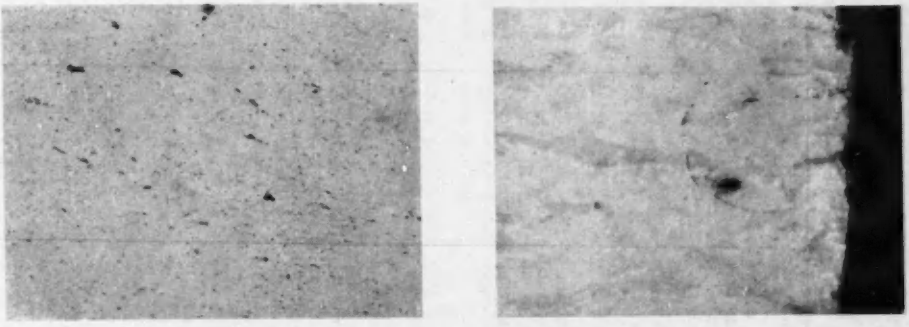


Fig. 6 (left). **Tank block which gave good service, showing close, dense texture ; contrast with upper photograph fig. 5. (Ground Section, approximately full size).**
(right). **Working face of the tank block after use (approximately full size). Contrast with second photograph fig. 5.**

* Sillimanite and Kyanite have the same theoretical chemical formula—$Al_2O_3.SiO_2$—but they are different minerals. They are converted into mullite—$3Al_2O_3.2SiO_2$—at different temperatures, the higher temperature being needed to convert sillimanite.

TABLE II.

The Constitution and Physical Properties of Tank Block Refractories for Glass Melting Furnaces.

	Fireclay Tank Blocks				"Sillimanite" Tank Blocks		
	Block A	**Block B**	**Block C**	**Block D**	**Block E**	**Block F**	**Block G**
Texture	Dense, close porcelain like texture with irregularly shaped holes between grains	Open Texture, grog not well bonded.	Open loose texture, cracks round grains of grog, many moulding faults.	Fairly well bonded but grains of grog easily distinguished.	Fairly dense, coarse grains of grog, well bonded; possibly too much bond clay used.	Fairly open texture, numerous pore spaces, sillimanite not well bonded. Apparently deficient in bond clay.	Close dense texture, grains of "sillimanite" well bonded with white burning clay.
Constitution as determined by X-rays—							
In "as received" condition.	Well developed crystals of mullite + vitreous phase of high silica content.	Poorly developed crystals of mullite + cristobalite + 30 to 40 per cent α quartz.	Poorly developed crystals of mullite + cristobalite + 20 per cent α quartz.	Poorly developed crystals of mullite + cristobalite.	Well developed crystals of mullite + α corundum + small proportion cristobalite.	Poorly developed crystals of mullite + cristobalite + about 20 per cent α quartz.	Poorly developed crystals of mullite + about 5 per cent each of cristobalite and α corundum + between 10 and 20 per cent cordierite.
In condition "refired at 1430—1450°C. for 5 hours."	Similar to "as received" condition; no change in size of mullite crystals.	Well developed crystals of mullite + cristobalite + siliceous vitreous phase.	(See footnote *) Comparatively well developed mullitecrystals + cristobalite + tridymite + trace of α quartz.	Well developed crystals of mullite + siliceous vitreous phase.	No change	Well developed crystals of mullite + cristobalite + vitreous siliceous phase.	Well developed crystals of mullite + vitreous phase.
Apparent Porosity. †AR	7.8%	26.9%	22.6%	19.4%	22.4%	17.8%	27.6%
True Porosity. AR	11.3%	27.6%	24.3%	20.7%	22.5%	18.9%	27.9%
Apparent Porosity. RF	2.8%	15.0%	—	8.7%	21.8%	13.6%	24.7%
True Porosity. RF	7.7%	17.7%	—	12.7%	21.8%	23.1%	25.1%

*—This specimen was refired at only 1350° C. †A.R.—"As received" condition. R.F.—Refired condition.

contain α quartz. This is unusual; the free silica is as a rule present either as α cristobalite or in the vitreous condition, but it should be emphasised again that the most reliable proof of adequate burning treatment is the presence of well crystallised mullite.

"Sillimanite" blocks frequently contain crystals of corundum, which were present in the original kyanite raw material. This free alumina is frequently not detected after specimens of such blocks have been refired in the laboratory, because it combines with some of the vitreous silica to form additional mullite. These changes also indicate that the burning treatment during manufacture was not as efficacious as that given in the laboratory.

X-ray examination is sometimes able to show that materials other than "sillimanite" and clay have been used in the manufacture of tank blocks. It has often been suspected that "fluxes" had been added to tank block mixtures in order to improve the texture and to reduce the porosity. Block G in Table II will serve as an illustration. In addition to the normal constituents: mullite, cristobalite and corundum, it was found to contain a proportion of cordierite, $2\,MgO.\ 2\,Al_2O_3.\ 5\,SiO_2$, which suggested an intentional addition of magnesia in some convenient form to the tank block mixture; during the burning operation the magnesia combines with some of the silica and alumina to form cordierite. Cordierite is not present, however, in the refired specimens. Experiments carried out in the laboratory have shown that cordierite formed in refractory materials breaks down to give mullite + a fluid glassy phase when the firing temperature is as high as 1430—1450 degs. C. The presence of cordierite in a block thus shows that the initial firing schedule is not the equivalent of laboratory refiring treatment of 1430—1450 degs. C. for 5 hours. Further the presence of this fluid glassy phase has been shown to be detrimental to high resistance to corrosive attack.

CORROSION OF REFRACTORIES BY MOLTEN GLASS.

Knowledge of such physical characteristics of tank blocks as texture, porosity and constitution are of importance but the final criterion is whether the blocks will withstand the attack of molten glass. Many tests have been devised in the laboratory for estimating the resistance of refractory materials to solution by molten slags and glasses, even to the building of small scale tank furnaces. The method used by the author consists in founding glass under specified conditions in a small crucible made by boring a hole in a suitable specimen of the refractory under test. The alumina content of the glass increases as it takes refractory material into solution, and this increase is taken as a measure of resistance to corrosion. This is expressed in terms of the amount of refractory dissolved in 100 grams of glass.

TABLE III.

Creep and Corrosion Tests on Tank Block Refractories.

Make of tank block	Relative resistance to corrosion	True volume porosity	Creep test data		Did failure occur?
			Temperature °C.	Rate of creep mms. per mm. per hour $\times 10^{-4}$	
K	1.0	15%	1350	100	Yes, after 2 hours
L	1.3	25%	1350	37	Yes, after 15 hours
M	5.1	13%	1350	0.8	Not in 350 hours
			1400	5.0	Yes, after 30 hours

The importance of porosity and texture as factors influencing the degree of resistance to corrosion has been emphasised by several workers; this is now well recognised, and examples have already been quoted. However, some blocks of low porosity and close texture are not as resistant as others and it is clear that the chemical problem of resistance to corrosion is more fundamental than that of macroscopic texture. This is illustrated by the results given in Table III. Blocks K and M possess close dense textures and are of low porosity, yet M is much more resistant to corrosion than K. An explanation for this difference in behaviour is found in the properties of the glassy matrix between the crystals.

* —This specimen was refired at only 1350° C. † A.R.—"As received" condition. R.F.—Refired condition.

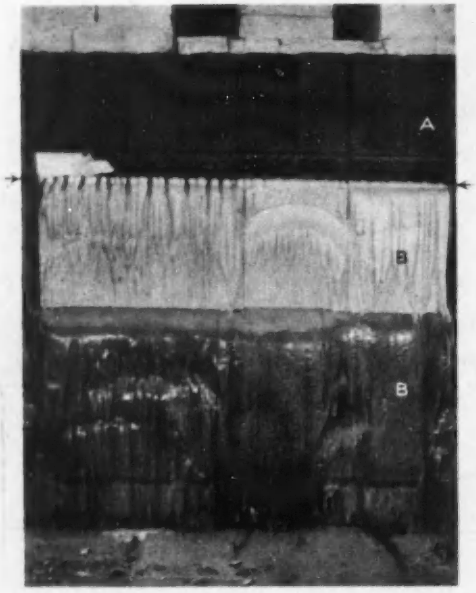


Fig. 7. Tank blocks (B) in the side wall of a glass tank furnace, illustrating the flow of material on them from the tuck stones (A) above.
Note fracture on the left showing that the staining is confined to the surface of the blocks above the glass level which is indicated by the two arrows at the sides of the photograph.

Refractory materials consist of crystals set in a glassy matrix; as shown in Table II the crystals in blocks for glass tank furnaces are mullite and silica in the form of quartz, cristobalite and tridymite, although corundum is sometimes present in "sillimanite" blocks. The glassy matrix arises from the combination of the "impurities" associated with the clay, with the silica set free when the clay decomposes on being heated. This glassy matrix serves to cement the crystals together and to reduce the porosity. The properties of a tank block are naturally related to the properties of the crystalline constituents as well as those of the glassy matrix.

During the life of a tank small pieces of refractory become detached from the blocks and are carried in the stream of molten glass to appear as minute "stones" in the finished ware. From an examination of these stones it is evident that the crystalline constituents of refractory materials are fairly resistant to solution, but little is known about the glassy matrix. In order to examine its properties at high temperatures, specimens cut from tank blocks were subjected to long time creep tests at 1350 degs. and 1400 degs. C. under the low tensile stress of 500 grams per sq. cm. The rate of extension or flow is a measure of the fluidity of the intercrystalline cement. The results given in Table III show that the glassy material between the crystals in some tank blocks is about 100 times as mobile as that in other makes of blocks; the blocks possessing the more fluid matrix were attacked more readily than those with the more viscous matrix, thus providing an explanation for the differences between certain types of block.

CORROSION OF TUCK STONES.*

Another source of contamination of glass in a tank furnace by solution of refractory material arises from attack by batch dust on the tuck stones. Tuck stones are set on the top faces of the tank blocks to seal the gap between the blocks and the furnace wall and so prevent the escape of flame. Comparison between furnaces at the beginning and end of their useful life (figs. 3 and 4) shows the extent of this attack. That products of the reaction have flowed into the glass is shown in fig. 7.

The formation of glassy material as the hot face of the tuck stone is approached from the cold face is seen from the results of X-ray examination given in Table IV. A pro-

Fig. 8. Tuck stones after use. Note spongy character of the fireclay tuck stones (B) showing that the material has drained from between the crystals and flowed into the glass. The first experimental silica tuck stone (A) has worn considerably less than the fireclay material.

* A fuller account of this subject was published in the *Journal of the Society of Glass Technology*, 1942, Vol. 26, p. 172.

TABLE IV.

Constitution of Intermediate Zones between Hot and Cold faces of 40 per cent Aluminous Fireclay Tuck Stones, illustrating occurrence of peritectic reaction mullite ⟶ alumina + siliceous liquid.

	Specimen	Constitution
Direction of increasing temperature ↓	Cool portion of Tuck Stone. "As received" state.	Mullite containing iron oxide and titania in solution + tridymite + cristobalite.
	Thick grey layer about 3 cms. from hot face.	Mullite + vitreous siliceous matrix.
	Thin black layer 1 cm. from hot face.	Mullite + α alumina + high proportion of vitreous siliceous matrix. Mullite has lost large proportion of iron oxide and titania impurities.
	Hot face of tuck stone consisting of brown layer about 1 cm. in thickness.	Open network of large crystals of α alumina + complex silicate of felspar type—mullite not detected.

nounced increase in the proportion of glassy material occurred and corundum appeared about 3 cms. from the hot face.

It is evident that the peritectic reaction occurring in the $SiO_2.Al_2O_3$ binary system in which mullite breaks down to form corundum + a siliceous liquid phase:

$$3Al_2O_3.2SiO_2 \rightarrow 3Al_2O_3 + 2SiO_2$$

Mullite → corundum + siliceous liquid

took place in this tuck stone refractory under the conditions obtaining in the glass tank furnace. This reaction occurs at 1810 degs. C. when pure materials are used, but the effect of impurities is to lower the temperature of the reaction. In this instance the impurities usually present in fireclay, assisted in all probability by the fluxing action of the batch dust, caused the reaction to take place at the comparatively low temperature of 1470—1500 degs. C. to which the tuck stones are exposed. The result of the peritectic reaction is the precipitation of corundum crystals and the formation of a siliceous liquid which is fluid enough to drain from between the corundum crystals and to flow down the faces of the tank blocks.

Impurities in the refractory had also migrated from the mullite crystals, and no doubt had assisted in increasing the fluidity of the glassy matrix. This matrix crystallised as the tuck stone cooled to form the complex silicate, but it must be borne in mind that at the operating temperature of the furnace it was fluid and had flowed down the inner faces of the tank blocks. Proof lies in the spongy character of the surface of the tuck stones, shown in fig. 8, and in the difference between the constitution of the brown layer on the surface of the tank blocks and the tank block material immediately beneath it, details of which are given in Table V.

Evidence of the fluidity of this intercrystalline glassy cement was obtained by subjecting a specimen cut from an unused tuck stone to the comparatively low tensile stress of 500 grams per sq. cm. at the temperature of the glass melting furnace, viz:—1400 degs. C. It failed immediately, so a second specimen was tested at 1350 degs. C. and this slowly extended at the rate of 0·01mm. per mm. per hour and failed after 2½ hours. Thus the glassy phase in this refractory was fluid at a temperature of 1350 degs. C., and

TABLE V.

Difference in Constitution between Tank Block Refractory and Layer of Material on its surface showing that the latter had flowed down from Tuck Stones.

Specimen	Constitution
Original Tank Block Material	Mullite in vitreous siliceous matrix
Brown Layer on surface of tank blocks	α alumina in vitreous siliceous matrix of higher iron content than that in the tank block material

TABLE VI.

Creep Tests and Corrosion Tests of Refractory Materials intended for Tuck Stone Service.

Specimen	Description	Creep test at 1350° C.		Corrosion test
		Rate of flow in mms. per mm. per hour	Failure	
A	Normal material 40% Al_2O_3. Coarse open texture.	0.01	After 150 minutes	Severe corrosion; deeply indented boundary between glass and refractory.
B	Siliceous material c. 22% Al_2O_3. Close texture.	0.001	No failure in 200 minutes. Failed after 60 minutes at 1400°C.	Attacked in least degree; some pitting of surface.
C	Aluminous material c.42% Al_2O_3; very coarse open texture.	0.03	Very rapid rate of flow while reaching 1350°C. Failed after about 600 minutes at 1350°C.	Most severely attacked of these specimens.
D	Silica material of fine texture c.95% silica.	Not measurable.	No measurable extension after 450 minutes at 1450° C.	Some deep pits; glazed appearance as though specimen had absorbed glass.

it is reasonable to suppose that it would be even more fluid under the conditions inside the glass tank furnace.

In order to try and effect an improvement in the behaviour of tuck stones, a number of materials was subjected to the creep test described above and specimens were tested for their ability to resist corrosion in the manner already described for tank blocks. Other things being equal, material of a siliceous character was to be preferred because it was known that less cord would be produced by its solution in the glass than by the solution of aluminous material.

A summary of the test results given in Table VI shows that some materials flowed at a faster rate than the normal material at 1350 degs. C. and therefore could not be expected to give a better performance in service. Silica was the only material tested which did not "creep" under the test conditions, presumably because the proportion of glassy phase present in lime-bonded silica material is small until temperatures in excess of 1600 degs. C. are attained.

Tuck stones are not in contact with molten glass, but they are attacked by batch dust, which presumably assists in the liquefaction of the glassy matrix which then flows down the surface of the blocks. Probably the best testing procedure would be to spray glass

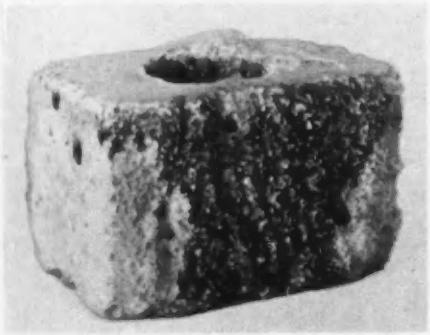


Fig. 9. Corrosion test of refractory material intended for tuck stones. Note that particles of refractory have become detached from the main body by the corrosive action of the glass.

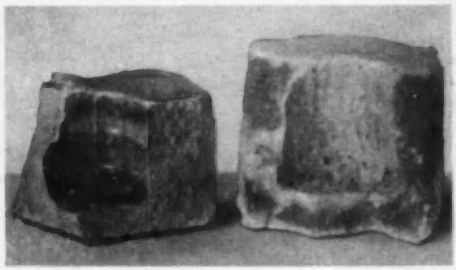


Fig. 10. Corrosion test of refractory materials intended for tuck stones. On the left is a sample of siliceous fireclay material (B), on the right a sample of silica material D.

making batch materials on tuck stones heated to the temperature attained in service, but as such apparatus was not available, the corrosion test was employed which has already been referred to in connection with the testing of tank blocks. The results are described in Table VI and illustrated in figs. 9 and 10. The siliceous material was more resistant than the aluminous specimens. Specimen C was a sample of a refractory material made with a bond clay unsuited for resisting corrosive attack because, as shown in fig. 9, the particles of grog became exposed after molten glass, due to overfilling, had flowed down the face of this specimen. The behaviour of the silica material was of special interest because it appeared to absorb the glass instead of being corroded severely, as was expected. Since its resistance to corrosion was higher than expected and its behaviour under the creep test was much more satisfactory than that of other materials, an experimental panel of silica tuck stones was installed in one of the tank furnaces. Its behaviour confirmed the laboratory tests in that the wear was much less than that of the normal 40 per cent aluminous material, as shown in fig. 11. This result was confirmed in other furnaces, and silica material has now been adopted for this service. The silica tuck stones remained almost the same size as they were originally, although they suffered some pitting. They possessed a closer texture and presented a glazed appearance after use, the porosity having fallen from 29 per cent before service to 11 per cent after service.

Fig. 11. Corrosion of tuck stones in a glass tank furnace. 1 indicates tuck stones of silica material D which gave better service than those of aluminous fireclay C, shown at 2.

Mobile Rectifier Substations.

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INTRODUCTION.

THE limited room available for mounting electrical equipment on road and rail vehicles provides a striking contrast to the spacious installations associated with the generation and distribution of electrical energy. The fact that a mobile substation can be produced to fulfil the same requirements as its stationary counterpart, is due to the static nature of the plant enabling it to be mounted on comparatively light structures—some examples of which are shown in fig. 1—unhampered by considerations of dynamic loading and heavy vibration. Each new electrical device gives rise to fresh problems peculiar to itself when required for operation on vehicles, and in this connection rectifiers have proved to be no exception.

Briefly, there are three main requirements to be satisfied: space, weight and ventilation. Each one has some bearing upon the others and it is by the successful compromise between all three that the most effective combination of compactness, portability and satisfactory operating conditions can be obtained.

Although this article is concerned primarily with air cooled steel tank pumpless rectifiers, it is proposed to make a passing reference to two other types, namely the water cooled and the glass bulb, as they have also been used in mobile substations, and serve to illustrate the design considerations involved. The conventional water cooled rectifier overcomes many of the limitations, and mobile rectifier substations built on railway wagons by various manufacturers are in use in America, Switzerland, Germany and Italy. These substations are usually mounted on double-bogie wagons carrying the rectifier transformer, the rectifier with its water and vacuum system and the A.C. and D.C. switchgear. The water cooling enables the single large tanks to be kept within a reasonable size and effectively disposes of the heat produced by the arc loss in the rectifiers. On the other hand, unless elaborate heat exchanging equipment is also fitted, operation

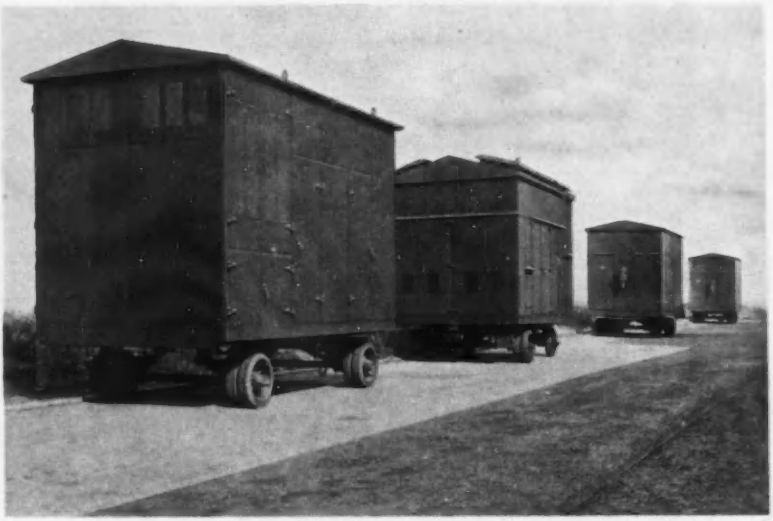

Fig. 1. A group of pumpless steelclad rectifier mobile substations for road transport, showing various arrangements of side and roof ventilation.

is restricted to those sites where a suitable water supply is available, and the water system needs careful attention if the substation is shut down out-of-doors in the winter months.

A more serious item is the weight of the equipment. The weights of water cooled rectifiers complete with auxiliaries, but without transformer, are from 3 to 7 tons for current ratings ranging from 1000 to 3000 amperes.

Weights such as these naturally tend to restrict water-cooled rectifiers to rail-borne substations in which specially sprung suspensions with insulated frames are used to mount these heavy rectifiers.

The glass bulb type of rectifier has also been tried, and substations of limited current outputs have been built for railway wagons. These rectifiers need special shock absorbing suspensions, but are free from the restrictions of water cooling and the vacuum pumping equipment. On the other hand, for reliable operation the bulbs must be conservatively rated, and as they need reasonable clearances between one another, the space required tends to be excessive even at moderate outputs. Another controlling feature, the reason for which will be apparent later, is the ventilation of vehicles containing rectifier bulbs cooled by open type fans with an uncontrolled air flow.

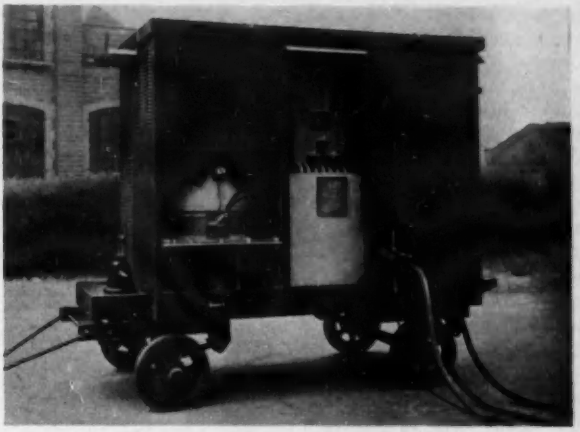

Fig. 3. 100 kW mobile unit giving a 220 volt D.C. two-wire supply, or alternatively, 50 kW at 110 volts.

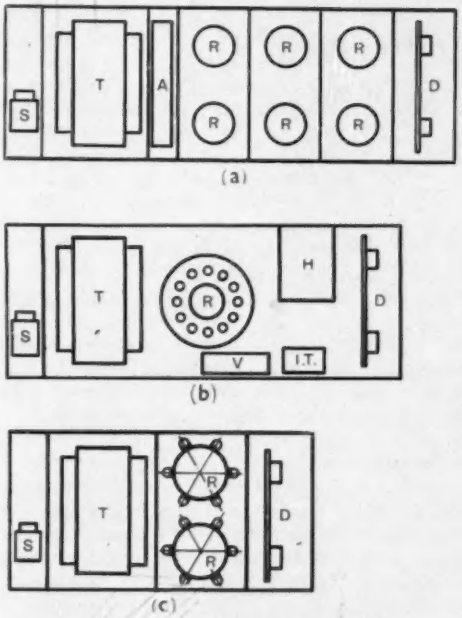

Fig. 2. Diagram showing the space occupied by a 1,000 kW, 500 volt substation, giving a two-wire D.C. supply, with standard overloads.
(a) Substation with six glass bulb units.
(b) Substation with water cooled rectifier.
(c) Substation with two pumpless steelclad rectifiers.

KEY.

S. Oil circuit breaker for incoming supply.
T. Main transformer.
A. Anode chokes.
R. Rectifier cylinders.
V. Vacuum pump.
IT. Isolating transformer.
H. Heat exchange for cooling water.
D. D.C. Switchboard.

The more intensive loading of the pumpless, steelclad rectifier, approaching as it does, that of the water cooled type, permits an appreciable saving in space. At the same time, the few auxiliaries needed simplify the layout considerably. As, however, the air serves both for ventilation and cooling, due provision must be made for the radiated heat and the scavenging of the rectifier compartment. If the proper factors are taken into consideration, it is found that not only can pumpless rectifier substations of useful outputs be housed on railway stock, but similarly rated equipment can also be mounted on road vehicles without exceeding the convenient limits of size and weight. Fig. 2 shows, by way of illustration, a comparison between the space required for three types of mobile rectifier substations of equal outputs with glass bulb, water cooled, and pumpless air cooled rectifiers respectively.

SOME APPLICATIONS OF RECTIFIER MOBILE SUBSTATIONS.

Mobile rectifying units find a number of uses both in peace time and during the emergency conditions imposed by war. To take a few examples :

(a) Service Uses.

Shipyards. Most ships use a D.C. supply at either 110 or 220 volts, two-wire, for lighting and general purposes, and while a ship is in dock, either for unloading or for repairs, it is convenient to use the permanently installed lighting system and other electrical services on shipboard, without having to run a generator on the ship. This can readily be done by connecting to a suitable shore supply. In the past this D.C. supply was frequently distributed from a fixed converting substation. This, however, has a number of disadvantages such as the size of D.C. mains necessary and the cable losses involved in a large dock or shipyard. A.C. distribution is much more economical either as a 400 volt, 4-wire system, or as a high voltage network.

Now, if a number of mobile rectifier substations are employed with suitable arrangements for supplying them from the A.C. distribution system, D.C. power at either 110 volts or 220 volts can readily be made available as and when required. A typical 100 kW equipment for this service is shown in fig. 3.

Permanent Standby Plant. A mobile unit can act as a standby for any number of substations, and such an arrangement is more economical than the present practice of installing in each substation a reserve rectifier of capacity equal to the largest unit. By reason of its mobility it can travel quickly from one place to another; and while this is important for existing groups of substations, it will be of even greater value in the economical planning of future D.C. supplies.

Fair Grounds. A considerable amount of power is needed to operate the many mechanical contrivances so popular in fair grounds. These are frequently driven from traction engines, donkey engines and other portable prime movers which are not very efficient, need a good deal of labour and usually give off much smoke and dirt. Mobile rectifier substations would have many advantages both from the point of view of the fair ground staff and the patrons.

(b) Temporary Uses.

Railway Systems. An electric traction system designed to give a successful train service in all circumstances usually includes a large proportion of standby converting plant. The total cost of the installation can be considerably reduced by having a number of mobile substations capable of being shunted into sidings at the various substation sites and of being quickly connected up to replace a unit in the substation which may be under repair. Furthermore, certain lines may occasionally be very heavily loaded to deal with the passenger traffic for important sporting events such as football matches, race meetings, etc., the extra trains causing heavy current demands. The addition of several mobile substations to back up the normal substations on these occasions is a convenient and economical method of dealing with such situations.

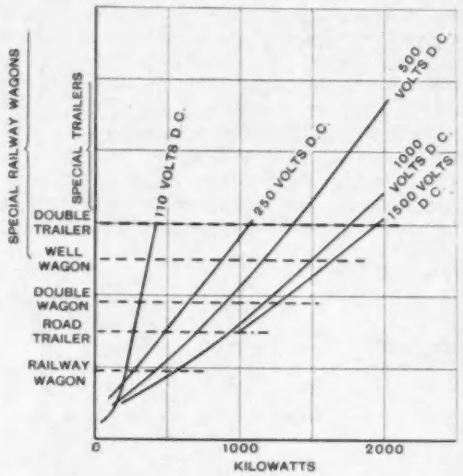

Fig. 4. Chart showing the relation between substation output and type of vehicle.

Exhibitions. In the layout of large exhibitions it is not uncommon to have several conventional substations housed in semi-permanent buildings. Space and expense can both be saved by resorting to rectifier mobile substations for the D.C. supplies required.

(c) Emergency Uses.

Mobile substations both on railway wagons and on road trailers find very many uses in war time. First, a number of factories can purchase jointly several mobile units designed for use on any of the factory sites, including railway workshops. In this way, standby equipment is available to replace quickly any substation destroyed by enemy action.

Secondly, mobile units have saved much inconvenience and loss of output by being used as standby plant during repairs to the existing plant. Again, the production output of a factory can sometimes be boosted in an emergency by increasing the power resources.

CONSIDERATIONS OF SPACE AND WEIGHT. Components.

Before discussing the various substation designs and components in detail, a glance at the following list of items may give a general idea of the equipment involved. The whole of the electrical gear will be carried on one or more vehicles, which may be either road trailers or railway wagons. The electrical gear includes the following apparatus :—

A.C. switchgear for incoming power supply.

Main transformer.

Rectifier cylinder or cylinders, including ignition equipment, surge absorbers, cooling fans, etc.

Rotary balancer (if required).

D.C. switchgear.

Earthing spikes, cables, tools, etc.

Once the output and the A.C. and D.C. voltages have been decided it is of immediate importance to determine whether the accommodation available is adequate for the substation components required.

In general, the convenient length for road trailers is less than 20 feet, and if this size is inadequate the equipment should be divided and housed in two vehicles. It is also desirable that the complete weight of a road trailer should not exceed about 15 tons. The total height of these vehicles cannot be stated with certainty as the height of road bridges varies tremendously. If, however, the height is not much more than 13 feet, it will be found that the majority of bridges can be negotiated. With rolling stock there are various standard covered goods wagons with four, and occasionally six, wheels and distributed loadings, between 10 and 15 tons. Then there are two axle well-wagons capable of providing a much larger housing and a loading of about 20 tons. Finally, there are very much larger and rather more special wagons with double bogies and loadings up to 60 or 80 tons. Any housings built on these wagons must, of course, be within the standard loading gauge imposed by the railway companies.

The size of a rectifier depends mainly upon its current rating and so also do the dimensions of the vehicle used for housing the rectifiers. On the other hand, the transformer dimensions are governed by the kVA requirements; moreover the transformer will be the largest single item in the wagon, and, to avoid freak transformer designs and unbalanced layouts, it is desirable to retain ordinary transformer dimensions so far as is possible. This may result in the transformer being mounted transversely or longitudinally, depending upon the circumstances. Again, it may be necessary sometimes to use a well-wagon to obtain the head room required.

The position with regard to the A.C. and D.C. switchgear is not so well defined. In the first place, the A.C. switchgear rating will be determined by the A.C. voltage and breaking capacity proper to the system short circuit impedance at all points where the connection to the A.C. network may be made. Generally speaking, the most suitable A.C. primary voltages are those up to 11 kV, and for the larger breaking capacities there will be little variation in the overall dimensions of a standard range of switches. For 22 and 33 kV supplies large clearances are required, so that both the A.C. switchgear and the transformer are relatively bulky. Road vehicles designed for this type of equipment become inconveniently large and awkward to manœuvre. This limitation is not so marked with railway vehicles. The D.C. switchgear will generally be for voltages below 600, and the space occupied by it will depend upon the output current rating and the number of feeder panels.

TABLE I.

	Rating.	Total cu. space required.	Floor Area.
	amps.	cu. ft.	sq. ft.
Rectifier	450	28	5
	600	44	7.5
	750	56	9.5
	1000	88	14
	kW		
Transformer	100	65	12
	300	150	21.5
	500	240	28
	1000	360	41
	MVA.		
A.C. Switchgear 3-ph. 11kV.	75 } 100 }	44	6.75
	150	47.5	6.75
	amps.		
D.C. gear*	500	16 (25)	3.5 (5.5)
	1000	20 (30)	4 (6)
With rotary balancer panel, see figs. in brackets	2000	37.5	7.5
	4000	70	14

* For 500 volts or lower.

Other items of plant mentioned in the list of components previously given can usually

be grouped underneath or alongside the main items, hence the total space required for the larger parts provides a datum from which the size of the vehicle can be estimated.

The case can perhaps be best exemplified by reference to Table I. which summarises the principal space data for the range of equipment likely to be used.

In applying this data it is necessary to consider the space factor, *i.e.*, the ratio of the total space required to the space actually occupied. For any permanent building housing machinery this ratio is comparatively high, partly for reasons of access and head room for lifting parts, and also on account of ventilation requirements. This value has been considerably reduced for mobile substations, and fig. 4 shows diagrammatically the housing requirements for substations of various voltages and outputs. The weight of the equipment is important for several reasons; first it determines the strength and the weight of the undercarriage required, secondly the type of wheels, and thirdly the weight distribution will determine the centre of gravity of the load, its stability and the axle loading. As it is the total weight which is of consequence, any contribution which will reduce the wheel base of the vehicle is as important as a direct reduction in the weight of the electrical equipment itself. In general, it must be assumed that the equipment may have to traverse soft ground and pass over inclined surfaces in the case of a road vehicle, and travel at reasonably high speeds in the case of railway equipment. These conditions imply that the weight distribution must be fairly uniform and the whole structure sufficiently rigid to be free from distortion.

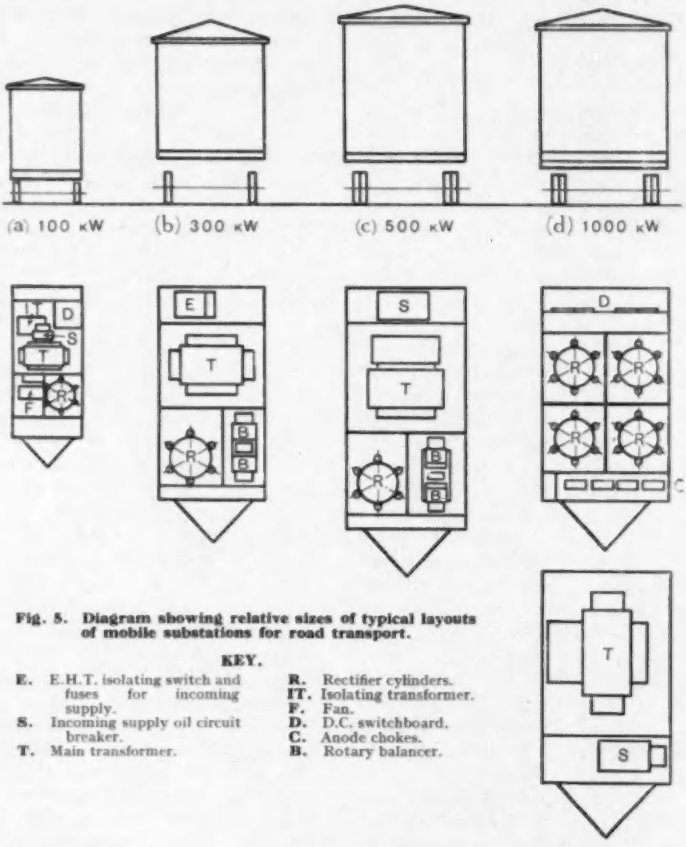

Fig. 5. Diagram showing relative sizes of typical layouts of mobile substations for road transport.

KEY.

E. E.H.T. isolating switch and fuses for incoming supply.
S. Incoming supply oil circuit breaker.
T. Main transformer.
R. Rectifier cylinders.
IT. Isolating transformer.
F. Fan.
D. D.C. switchboard.
C. Anode chokes.
B. Rotary balancer.

SOME TYPICAL SUBSTATION DESIGNS.

From the foregoing an indication has been given as to whether the equipment is likely to

require one or two vehicles. Where substations have to be divided, the A.C. switchgear and the main transformer can be housed conveniently on one trailer and the rectifier and the D.C. gear on the other.

In most instances the partition of the gear between two vehicles is fairly obvious ; in the event of certain additional items being required, such as anode chokes and rotary balancers, these would preferably be housed in the D.C. vehicle. On the other hand, features such as smoothing chokes, tension limiters and grid control gear could be accommodated

Fig. 5 shows how the layout changes as the size of the substation increases through a number of typical ranges, starting with the lower outputs. The smaller substations are of the single wagon type, and the problem in the case of these vehicles is to counterbalance the preponderating weight of the transformer, either by mounting it transversely with the rectifier on one side of it and the switchgear on the other, or alternatively, the wheels can be offset to permit the rectifiers to occupy a central position between the transformer and the switchgear.

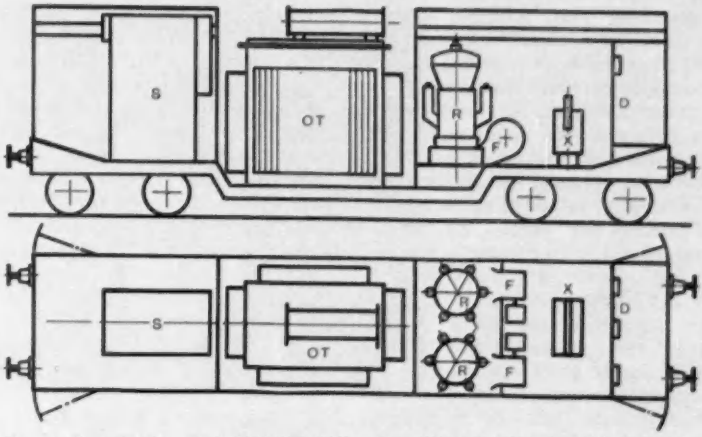

Fig. 6. Projected layout of 2000 kW, 1500 volt mobile substation for rail transport.

KEY.

S. Incoming supply oil circuit breaker.
OT. Main transformer (outdoor).
R. Rectifier cylinders.
F. Fans.
X. High speed D.C. circuit breaker.
D. D.C. switchboard.

in either vehicle according to the space available. It may be necessary to install the grid control gear in the A.C. vehicle to prevent the D.C. vehicle becoming unduly crowded with a number of small components. Conditions can often be simplified by diverting some of these to the A.C. part of the equipment.

Another factor which influences the details of the layout is whether access to the interior of the vehicle is desired either on or off load. Usually the substation, once switched in, can be operated unattended, so that those using the station need have access only to the A.C. circuit breaker which can be conveniently mounted at one end. In the case of mobile units for railway working, it is desirable that the substation be operated from within, so that there is less risk to operators from traffic on the tracks adjoining the siding into which the station is shunted.

With substation outputs of 300 kW the equipment can be mounted on a simple four wheeled truck with single wheels. For these low outputs the A.C. supply will probably be at 415 volts, and elaborate switchgear becomes unnecessary. Cable runs are short, and the cable sizes small, so that there are few restrictions upon the design.

Above 300 kW, E.H.T. supplies of 11 kV and 6·6 kV have to be considered. The increased weight of the A.C. switchgear, the heavier current D.C. switchgear and the larger rectifier enable a more reasonable balance to be maintained with the transformer weight.

At 500 kW, not only has a wide range of A.C. voltages to be contemplated, but also the choice of D.C. voltages may require more than one rectifier cylinder. At 500 volts D.C. a single 1000 amp. cylinder would suffice, and in this case an effective arrangement can be laid out as shown.

The space alongside the rectifier can be used for accommodating the D.C. panel, and in the event of a three-wire supply, the rotary balancer can be mounted below and behind the panel. The height available enables the main oil circuit breaker to be housed in a compartment by itself, with ample room for operating the switch by hand and under cover. With a 250 volts D.C. output, two rectifier cylinders will be required together with anode chokes. The two cylinders occupy an end compartment with the anode chokes and D.C. panel arranged transversely between them and the main transformer, the A.C. and D.C. switchgear being on the other side of the transformer.

For sizes above 500 kW, 500 volts D.C., it becomes necessary to consider the use of two vehicles, for example 1000 kW at 230 volts D.C. requires four rectifier cylinders, and these together with the anode chokes and D.C. switchgear take up most of the space in one trailer. Furthermore, additional features such as anode busbars and cable connections have to be considered. The transformer is also becoming fairly heavy, and this together with the larger A.C. switchgear, and the need for space to bring the anode cables in the correct sequence from the transformer results in two trailers of nearly equal size.

The foregoing discussion has been with reference to road vehicles, but slightly different conditions apply to rolling stock, of which three examples are shown in figs. 6, 14 and 15. Consider, for example, a 500 kW substation in two standard goods wagons. A suitable method of arranging the rectifier wagon is that of mounting the cylinders approximately over the axles with the D.C. switchboard between the rectifiers. The transformer and A.C. switchgear are mounted together in a second similar wagon, and the cables and connections carried through the facing ends of the two respective wagons.

If a special well-type wagon is used, much larger substations can be accommodated on one vehicle, and the limit tends to become the axle loading rather than the space required. For example, a four wheeled well-truck is easily capable of containing a 1000 kW substation. Actually it may not be necessary to enclose the transformer, which will then be of the out-door type, and the kiosk part of the vehicle will contain the rectifier cylinders, A.C. and D.C. switchgear, rotary balancer, if required, and all the auxiliary gear.

For a 2000 kW, 1500 volts D.C. substation, the arrangement could be split up between two large wagons; or a special double-bogie wagon would be constructed. It is inevitable that the weight of such an equipment would be increased, due not only to the electrical gear, but also the deep girder sections necessary to carry the weight on the larger span between the supports. The problem is, however, within possibilities, and fig. 6 shows a projected arrangement for this size of substation, assuming a 33 kV E.H.T. supply and a circuit breaker with 500 MVA breaking capacity.

MECHANICAL CONSIDERATIONS.

The mechanical considerations can be divided into two groups, one is concerned with the strength of the vehicle, its riding qualities, the means for providing the necessary stiffness without increasing weight to an excessive degree, and the type and arrangement of the suspension, wheels, brakes and towing gear; the other is concerned with the suitability of the parts to withstand transport and the means for securing them in position so as to resist sudden braking and acceleration, without excessive vibration being transmitted during travel.

The weight of the housing, especially with road vehicles, must be kept to a minimum. The body of the wagon which carries the decking consists of a welded framework of longitudinal and transverse members of suitable rolled steel sections. The main members are placed to take the whole of the weight of the heavier components. The top of this frame is then covered with a relatively light steel plate decking on which the apparatus is mounted. The wagons are mounted upon semi-elliptical springs, the wheels and towing arrangements varying according to the type of substation and whether it is intended for road or rail service. For rolling stock, the running conditions are taken care of in the design of the permanent way. The stability and ease of riding depend upon the position of the centre of gravity with respect to the wheel base, and, in this respect, the mobile rectifier substations are favourably placed, as it is possible to produce a balanced layout without departing from a reasonable electrical arrangement. On the roads, however, the conditions are not so well defined; it is conceivable that the trailer may have to traverse unmetalled roads and heavily cambered surfaces or uneven ground; moreover, it may have to be manoeuvred between buildings where the space is strictly limited. To overcome these difficulties, it is

the practice to provide two pairs of wheels on each axle when the weight demands it and to arrange a suitable wheel base with a wide locking angle to give the minimum turning circle. At the same time, to provide the maximum stability, the track is kept as wide as conveniently possible, the tipping angle for the road vehicles being about 30°. By way of example, a substation on a wheel base of 10ft. 6in. and a track of 6ft. 8in. can be turned practically in its own length.

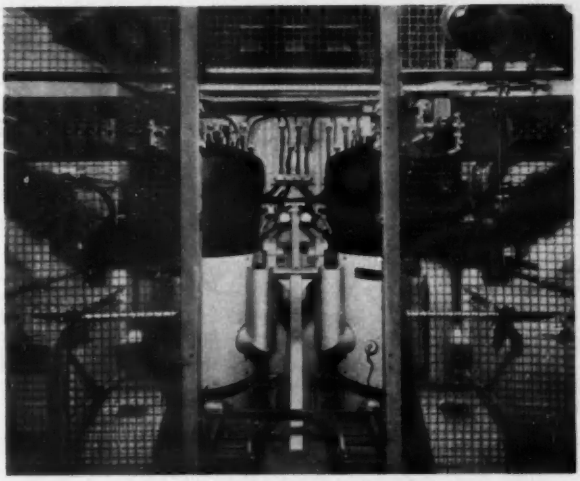

Fig. 7. Interior of rail substation showing trunnion mounting of pumpless rectifiers.

The deck of the vehicle should be kept as low as possible to give a maximum height for the accommodation of the equipment. On the other hand, for easy manoeuvring over rough ground large diameter wheels are desirable; it is therefore obvious that a compromise has to be struck. A height of deck not exceeding three feet seems to be the most suitable, and to accommodate the wheels under this, solid rubber tyres appear to be better than pneumatic tyres. It must be admitted, however, that due to present conditions the question of using pneumatic tyres has not been very fully explored.

When conditions indicate the likelihood of jacks being needed while the substation is in operation, or parked for storage, a number of these can be built in at suitable points around the base of the truck. By jacking on to timber or suitable metal plates they can also be used to prevent the trailer from sinking in when parked on soft ground.

For general safety, both in travelling and when parked on an incline, the wheels are provided with adequate brakes of the internal expanding type which can be operated either by hand or automatically through a lanyard connected to the towing vehicle, in the usual manner.

The special mechanical requirements for the electrical equipment mounted in the substation are lessened considerably by the efficient springing of the vehicle and its rigid construction. A pumpless steel tank rectifier has particular advantages against vibration; the all metal construction enables the cylinder to withstand any mechanical shock resulting from the swishing of mercury. Furthermore, as the cylinder is held rigidly to its supports, any low frequency mechanical resonance is avoided.

The speeds at which very heavy vehicles such as these substations can travel on the roads are comparatively low, and the normal method of supporting the cylinder has proved completely adequate.

Rail borne equipment has to withstand much more severe treatment, and allowance has to be made for high braking speeds and impact during shunting, in addition to other forms of mechanical strain produced by the swaying and jolting of the vehicle. These difficulties have been successfully overcome by suspending the rectifier cylinder on trunnion bearings whose axis passes through the centre of gravity of the cylinder,* see fig. 7.

Service experience has fully confirmed the reliability of the rectifiers and their ability to withstand being transported as part of a mobile substation and to be immediately available for service.

VENTILATION AND COOLING.

To ensure reliable operation under all weather conditions, it is essential to maintain a stable balance between the heat received, both internally and externally, and the dissipation. At first sight, it would appear that, provided the cooling can be maintained under overload conditions during the maximum summer temperatures with the substation also exposed to the direct radiation from the sun, the results would be entirely satisfactory. Actual experience has shown, however, that the best results are obtained with reasonably

* Patent applied for.

constant conditions inside the substation itself, and with due allowance for winter as well as summer weather.

The main sources of internal heating are the transformer copper and iron losses, the

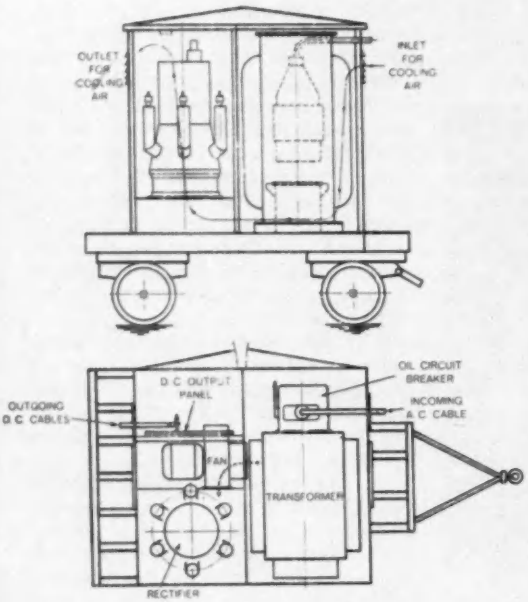

Fig. 8. Diagram showing system of ventilation for small units.

rectifier arc losses and sundry auxiliary losses ; and for their effective dissipation there is available forced cooling, radiation and natural convection. In practice, the substation will be designed to meet the requirements of a specification in which the usual arrangement is that the temperature in the substation shall not rise more than a prescribed number of degrees above the surrounding air. Under overload test conditions, which may be a 25 per cent overload for two hours, the temperature will be changing all the time, so that the problem is really a dynamic one.

The circumstances are somewhat different from those usually appertaining to the cooling of electrical machines, inasmuch as the heat is being dissipated over a wider range of temperatures in the case of rectifiers with side arms. An idea of the quantities involved can be gathered from an analysis of the losses in a 500 kW, 500 volt equipment. The efficiency at 25 per cent overload of such a plant would be about 92·5 per cent, *i.e.*, the losses will amount to 37.5 kW. In the case of the transformer, the losses will be transferred at a mean surface temperature of about 50 degs. C. from the large area presented by the cooling tubes, and most of the heat will be carried away by convection. The rectifier tank will be at about 60 degs. C., while the anode arms have a high operating temperature and the thermal radiation will be fairly intense. It is estimated that about 6 kW of energy will be radiated directly from their hotter parts to the walls in a space comparable with a fairly small room. On a cool day, the greater part of this heat will be transferred to the external air, but on a warm, still day, the internal and external heat transfers may be more or less equal. In general, the rectifier compartments will have two outside walls, so that a dissipation of 0·3 watts per sq. inch on either side will provide a total removal of radiated heat of roughly 0·6 watts per sq. inch, *i.e.*, 20 sq. ft. of cooling surface will cope with the radiated heat from the rectifier without the wall temperature exceeding 45 degs. C. It should be noted that this calculation allows for a return of 3 kW to the cooling air inside, which will be in addition to that normally removed by forced cooling.

If, for the moment, the actual details of the heat transfer are ignored, we can say that cooling air will be required to deal with 34·5 kW, so that if the temperature rise is not to exceed 20 degs. C, 3 to 3½ changes of air per minute will be required to maintain stable conditions. In the event of a wooden enclosure with cavity walls, as, for example, a standard goods wagon, all the heat will have to be removed internally, and 4 to 4½ changes of air will be necessary every minute.

There are several methods of arranging the air flow conditions to provide the desired ventilation, and the selection of any one method depends upon the layout of the equipment. One method, shown in fig. 8, is to design the respective compartments so that the cooling air flows through them in series, and cools each component in turn. The temperature rise of the air on leaving the transformer compartment is only a few degrees above the ambient temperature, and is without prejudicial influence upon the efficient cooling of the rectifier cylinder.

An alternative arrangement is to separate the transformer and rectifier compartments completely, and to provide suitable inlets in the floor to allow the natural draught to cool the transformer. The air inlet grilles are located directly beneath the transformer cool-

ng tubes, and thus the transformer acts as its own draught inducing device.

A third solution is provided by having an outdoor transformer and housing only the rectifier and the switchgear. In this case, only the heat losses from the rectifier need be considered, the quality of cooling air will depend upon the current rating and the flow will be supplied by the rectifier fan.

An important consideration is the temperature rise of the rectifier cylinder and the maintenance of a proper temperature distribution over the surface. It is known that in all rectifiers the arc voltage and the reliability are influenced by temperature, therefore it is essential that the proper relation be established between the arc losses and the heat dissipation to maintain the optimum working conditions. In view of these facts, the circulation of air inside the vehicle becomes important.

Finally, the question of outside temperature variation between summer and winter conditions has to be taken into account. It is obvious that a mobile substation, exposed on all six faces, will be much more sensitive to these changes than a permanent building, and to maintain the rectifiers at their optimum working temperature use is made of a damper fitted in each fan intake and set by hand.

WEATHER TIGHTNESS.

In view of the provision of louvres and grilles for ventilation, special attention must be paid to the weather tightness of the mobile substations. The chief risks are from driving rain and drifting snow, particularly when the substation is not actually in use. To minimise these dangers, it is essential that any roof openings be provided with a deep coaming to keep out water; also all openings must be covered with suitable wire mesh to prevent the entry of birds and vermin. In addition, the panels which cover the roof openings should be given a generous overhang; this also applies to the roof itself where ventilation openings are used under the eaves. Where side louvres are used to discharge the air they should be designed to shed the rain, although this means that the warm exit air will be deflected downwards.

Weather protection must also be given to cable connections, and for this reason either special cable spouts are used for the individual leads or alternatively a cable "flap" is arranged, consisting of a sheet metal structure which collapses so as to be flush with the body of the wagon when not in use, and which is hinged to provide a weatherproof opening for the cables when required. Doors and other openings are conveniently made weather tight by the use of suitable seatings against which they are closed and clamped down in position.

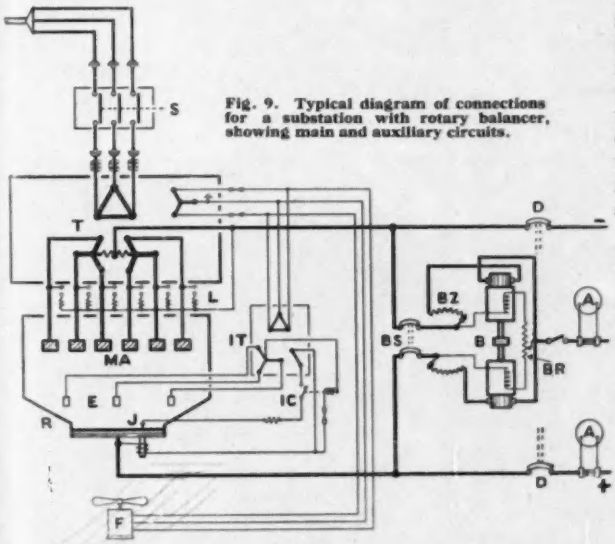

Fig. 9. Typical diagram of connections for a substation with rotary balancer, showing main and auxiliary circuits.

KEY.

S.	Oil circuit breaker for incoming supply.	**IC.**	Ignition contactor.
T.	Main transformer.	**F.**	Fan.
L.	Tension limiters.	**D.**	Main D.C. circuit breakers.
R.	Rectifier cylinder.	**A.**	Ammeters.
MA.	Main anodes.	**B.**	Rotary balancer.
E.	Excitation anodes.	**BS.**	Balancer circuit breaker.
J.	Ignition anode.	**BZ.**	Balancer starter.
IT.	Isolating transformer.	**BR.**	Balancer field regulator.

THE ELECTRICAL EQUIPMENT.

To reduce the weight and size of the equipment to a minimum, the simplest possible electrical gear should be used which will be reasonably convenient and perfectly safe to operate in all weathers.

A typical diagram is shown in fig. 9. The main transformer and rectifier cylinder, or cylinders, are necessary, and their size and form for a given loading cannot be varied to any extent.

Various forms of A.C. switchgear are available.

(*a*) Outdoor isolators and E.H.T. fuses.

(*b*) Outdoor isolators and outdoor main oil circuit breaker.

(*c*) Indoor isolators and E.H.T. fuses.

Fig. 10. End view of mobile substation showing E.H.T. switchgear, comprising oil immersed isolator and E.H.T. fuses for 11kV.

(*d*) Outdoor metalclad gear, including main oil circuit breaker.

(*e*) Indoor metalclad gear including main oil circuit breaker.

(*f*) Indoor S.V.D. switchgear, including main oil circuit breaker.

(*g*) Indoor air insulated cubicle type gear, including main oil circuit breaker.

It will be noted that the possibilities listed above fall into two main classes, namely, equipments including a main oil circuit breaker and equipments including only an isolator, capable of breaking full load current, and E.H.T. fuses for protective purposes.

The circuit breaker equipments are naturally more bulky, heavier and more expensive than the fuse equipments, but, in general, experience has shown that the circuit breaker is worth while, and gives better protection as well as ease of adjustment of the overload settings, and after a fault, the service can be restored more quickly.

The choice of the form of the E.H.T. gear depends on a number of site conditions of which distribution voltage and the severity of the fault currents on the system are the most important.

If, for instance, the mobile equipment is to act as a standby on a railway system for traction substations fed by overhead lines, then outdoor isolators and an outdoor oil circuit breaker would be suitable. In such cases, live exposed terminals can readily be screened to prevent accidental contact. On the other hand, if the mobile equipment is to replace a factory substation which may be damaged by enemy action, the opportunities of effectively screening live terminals are not good and the connection will normally be by underground cable. Here one of the indoor types will probably be most suitable. Typical examples of indoor type switchgear incorporating both E.H.T. fuses and oil circuit breakers are shown in figs. 10 and 11.

D.C. switchgear will nearly always take the form of a flat-back switchboard panel, or panels, housed within the kiosk structure, fig. 12. The usual substation practice is to have an input circuit breaker between the rectifier and busbars and a number of feeders, each protected by circuit breakers from these busbars. For standby purposes it is usually sufficient to use only the rectifier circuit breaker and to feed direct from this to the distribution network.

Frequently a three-wire D.C. system has to be supplied, and this can be done either by using two rectifier cylinders in series for

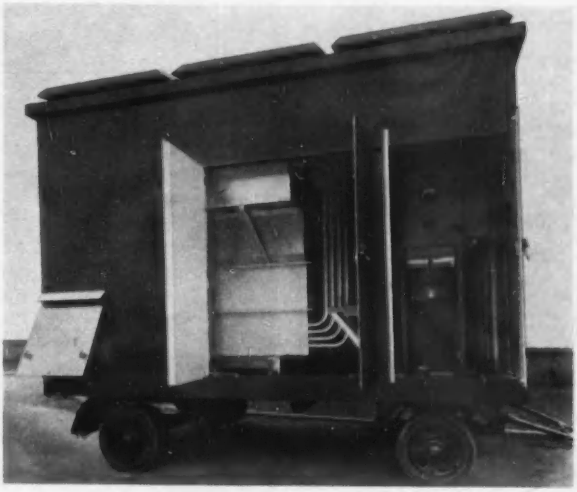

Fig. 11. Side view of mobile substation showing E.H.T. switchgear with air insulated vertical drop down indoor type oil circuit breaker

balancing purposes, or by a rotary balancer. Again, local conditions may determine which system is adopted, but usually, the most compact and lightest arrangement is obtained with a rotary balancer, which will be connected to the rectifier, and the switchgear arranged so that the D.C. network cannot be supplied unless the balancer has been started and is ready for load.

AUXILIARY EQUIPMENT.

Sundry auxiliary equipment must be catered for, the most important being :

(*a*) Control of cooling fans for the rectifier cylinders.
(*b*) Ignition arrangements.
(*c*) Auxiliary anode (or excitation) circuits.

The necessary A.C. supply for all these circuits is usually obtained from a tertiary winding on the main transformer, which gives a 3-phase supply at 230 volts. As this circuit becomes alive only when the main transformer is energised, switchgear can, in general, be dispensed with, the auxiliaries being directly connected to the tertiary. This means that the fans will start up immediately the main transformer is energised, and ignition takes place at once, causing the auxiliary anodes to strike. Thereupon a relay in the auxiliary anode circuit operates automatically and de-energises the ignition circuit. To protect the equipment, an overload relay in the fan circuit will operate to give an alarm, or to trip the main oil circuit breaker, in the event of failure. The ignition and auxiliary anode circuits are protected by fuses, and are fed through an isolating transformer.

OPERATION.

The question of the safe operation of mobile substations of this class needs consideration. First, the whole structure is small and made of steel; secondly, in many cases they may be handled and operated from wet ground. The structure must therefore be well earthed, preferably to a permanently established earthing system or, failing this, by driving at least two spikes into the ground, one being placed on each side of the substation.

From the point of view of safety in operation, it is advisable that exposed live metal should be eliminated as far as possible from the switching compartments. Compartments which are not used for these operations should be kept closed and locked when the equipment is in service.

If necessary, certain doors and switches can be interlocked to prevent accidental contact with live metal, particularly when E.H.T. fuses are used instead of an oil circuit breaker. In this case, it is advisable to interlock the fuse compartment with the E.H.T. isolator, so that access to the fuses can only be obtained when the isolators are open and the E.H.T. side of the rectifier transformer is earthed. In many instances the equipments can be operated entirely from the E.H.T. side of the main transformer. After connecting the D.C. side to the load, the D.C. circuit breaker is closed and the door of this compartment locked. The supply of D.C. power can thus be switched on or off as required by means of the oil circuit breaker.

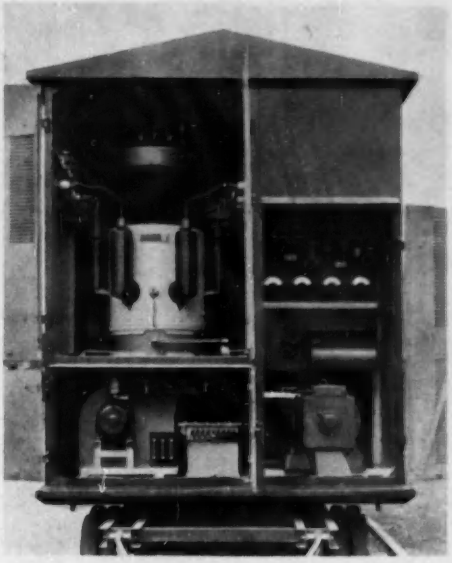

Fig. 12. A 500 kW single-trailer mobile rectifier substation showing rectifier cylinder, D.C. control gear and rotary balancer.

TEMPORARY CONNECTIONS.

The design of this type of substation requires the use of temporary electrical connections. As the D.C. output is usually at a relatively low voltage, tough rubber covered flexible or semi-flexible cables are very satisfactory and are, in fact, the only really convenient form of connection. The same applies to anode leads which may be necessary if the transformer and rectifier cylinders are housed in separate vehicles, and is true also of A.C. cables if this supply is at low tension.

A greater degree of protection is necessary

Fig. 13. A 920 kW rectifier mobile substation, showing two of the four cylinders with auxiliaries.

for the E.H.T. connection. A tough rubber insulated cable does not give sufficient protection unless it is screened or armoured, and such screening or armouring makes the cable heavy and reduces flexibility.

Another suggestion is to have bare leads suitably screened. This arrangement is very convenient and adaptable if the E.H.T. supply is being taken from an outdoor substation where temporary screening can be readily carried out in the neighbourhood of the mobile unit.

More frequently the E.H.T. distribution is carried out with paper insulated and lead covered cable. There is then the further complication of having to terminate this cable suitably to take the bare connections which also need screening. In such cases, the E.H.T. can probably be most quickly connected to a proper sealing box on the kiosk with a normal wiped joint. If this is done there is no question of screening live connections and a perfectly sound and safe weatherproof connection is made.

SOME TYPICAL MOBILE SUBSTATIONS.

The following brief description of the typical rectifier substations shown in the accompanying illustrations should prove of interest, as the units described are actually in operation under service conditions.

The first example is a fairly large double-wagon substation rated at 920 kW with overloads, converting from 11 kV or alternatively 6 kV, 3 phase A.C. to 230 volts D.C.; the full load current of 4000 amperes is shared between four D.C. panels. An external view of the rectifier trailer is shown in fig. 13, while the internal layout is generally as indicated in fig. 5(*d*). The compartments are housed in two fabricated steel trucks with boiler plate sides and roof and stout oak floors provided with suitable ventilation inlets. Each truck is spring mounted where necessary on double wheels, the front pair swivelling with the draw bar. All the wheels have solid rubber tyres, cast steel hubs and are free to

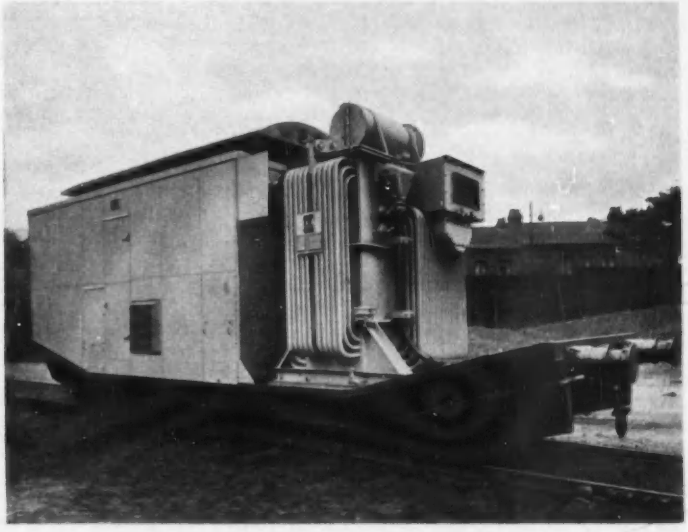

Fig. 14. A 1,000 kW, 500 volt, mobile rectifier substation for railway workshop supply.

rotate on the fixed stub axles. Internal expanding brakes are fitted and can be operated either by hand or automatically from the towing vehicle.

At the other end of the scale, there are the small 100 kW units for conversion from 415 volts, 3 phase A.C. to 220 volts or 110 volts D.C. One of these mobile units, as illustrated in fig. 3, consists of a small pumpless rectifier together with its transformer, switchgear and auxiliaries mounted on one truck. All external connections are made through earthed and shielded fittings with robust metal cases and provided with hand grips.

A mobile substation, one of a number built to the requirements of a British railway company, is illustrated in fig. 14. It consists of a standard, two axled well-wagon, carrying a 1000 kW, 500 volt, 3-wire D.C. substation. The outdoor type of transformer is arranged for 11 and 6·6 kV, 3-phase supply, but the switchgear and 1,000 ampere rectifier cylinders are all housed in the welded boiler plate kiosk. The air intake louvres can be seen on the sides of the wagon, and the special weatherproof roof arrangement is designed to deal with the warm air from the inside. Access to the operating platform is through a door on either side and the operators can carry out all the A.C. and D.C. switching, control the rotary balancer and take the necessary meter readings under cover. An external emergency trip is provided for shutting down.

A 500 kW substation for another railway company is shown in fig. 15. This unit is arranged to give either 2000 amps. at 250 volts or 1000 amps. at 500 volts. The equipment is accommodated in two standard goods wagons of the double walled type, suitably ventilated to meet the requirements of the air cooled rectifier and the transformer. "Jumper" cables are provided for the anode and auxiliary connections between the two wagons. The transformer and A.C. switchgear are housed in one wagon, while the rectifiers are mounted on either side of the D.C. panel in the second wagon.

The foregoing descriptions by no means exhaust the types and varieties of mobile substation constructions. There seems no limit to their adaptability, and the purposes to which they can be applied. Although partly introduced as a war time measure, it is confidently anticipated that they will find equal, if not greater, scope in the reconstruction period in peace time, particularly as their electrical performance and efficiency are equal in every way to that of a standard substation of the corresponding rating.

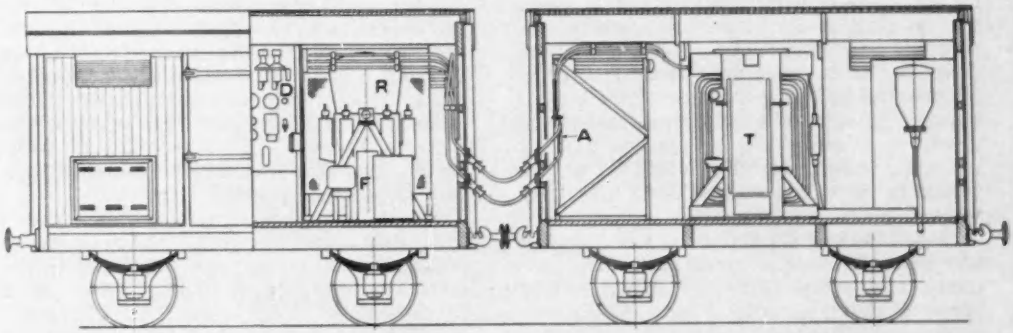

Fig. 15. General arrangement of a 500 kW, 500 volt, alternatively 250 volt, double-waggon substation.

KEY.

T. Main transformer. **A.** Anode cables. **R.** Rectifier cylinders. **F.** Fans. **D.** D.C. switchboard.

Miniature Film (Mass) Radiography.

By A. J. MINNS,

Watson & Sons (Electro-Medical), Limited.

1. INTRODUCTORY.

A COMMITTEE appointed by the Medical Research Council to investigate tuberculosis in war time has recently published its report.[1] It reveals that, during the war years, deaths from tuberculosis have increased considerably, and makes practical suggestions on means to bring about an improvement. One of the principal recommendations which is being put into immediate effect is the adoption on a nation-wide scale of radiography of the chest on miniature film by means of the apparatus which forms the subject of this paper. Before proceeding to a description of the method and of the apparatus, a brief outline of the circumstances which led the Committee to place great faith in its effectiveness will be of interest.

Taken in its early stages, pulmonary tuberculosis responds well to appropriate treatment and the patient has a very good chance of complete recovery; if unchecked, however, the chances of recovery are slight. Unfortunately, tuberculosis very often advances beyond the early stages before the sufferer is aware that anything is amiss, and even a thorough medical examination by ordinary clinical methods frequently fails to reveal symptoms of infection before the disease has advanced beyond the stage at which it will respond to treatment. During the early stages, too, the unwitting sufferer may be passing on the infection to his fellow workers and others with whom he comes into contact.

One of the best known methods of detecting incipient tuberculosis with reasonable certainty is by means of x-rays, and as will be appreciated, it is necessary in order to discover unsuspected lesions, to examine persons who are to all outward appearances enjoying normal health. To examine large numbers of persons by ordinary x-ray methods, however, is impracticable because it is a time-consuming process and, moreover, involves the use of films measuring 15 × 12 inches. Such films are quite expensive and their processing, storage and filing when carried out on a very large scale present many problems. Miniature film radiography affords the means of making x-ray examinations at great speed and at comparatively small expense, and thus can be applied as a routine measure regardless of the number of patients involved.

The method employed is by no means new,[2] having been visualised within a few months of Roentgen's discovery of x-rays in 1895. Only in the last few years, however, has it been possible to produce films of a sufficiently high quality to justify the universal adoption of this procedure. Before describing the method, an outline of the means used to produce full size radiographs is given.

2. PRODUCTION OF FULL SIZE RADIOGRAPHS.

The method of producing radiographs both in medicine and in industry is now well known. Briefly, the object to be radiographed is placed in contact with an x-ray film which has been previously enclosed in a light-tight envelope or cassette. An x-ray tube is positioned with respect to the film and object in such a manner that the radiation passes through the object usually in a direction normal to the plane which it is desired to view. Varying thicknesses and densities in the object produce corresponding variations in the quality and quantity of radiation reaching the film, the process resulting, on development, in an image of the object in which differing thicknesses and densities are represented by varying film blackening. The blackening of the film results from absorption of x-rays in the emulsion.

X-rays having sufficient penetrating power to enable a radiograph of the chest to be produced, will not be greatly absorbed in the comparatively thin emulsion, even on a heavily coated film, and in modern x-ray technique it is customary to make use of "intensifying screens." These consist of sheets of thin card coated with an even layer of a finely ground substance capable of fluorescing under the action of x-rays. Films coated on both sides are used, with an intensifying screen clamped firmly against each of the sensitive coatings. The film blackening during an exposure is then produced partly by visible light excited in each of the screens, and partly by absorption of x-rays in the emulsion itself. In this manner the exposure

time for a given set of conditions is very greatly reduced.

When it is not considered necessary to make a permanent record, a visual x-ray examination (screening) can be carried out by examining the visible image produced on a fluorescent screen of similar construction to the intensifying screens referred to above. The screen is usually covered with a sheet of lead loaded glass which absorbs any radiation passing through the object and the screen.

3. PRODUCTION OF MINIATURE FILMS.

Fig. 1 shows the essentials of an apparatus for miniature film radiography. The x-ray tube, patient, fluorescent screen and lead-glass occupy the same relative positions as in a visual screening examination. A secondary radiation diaphragm (described later) is placed between the screen and the patient and prevents

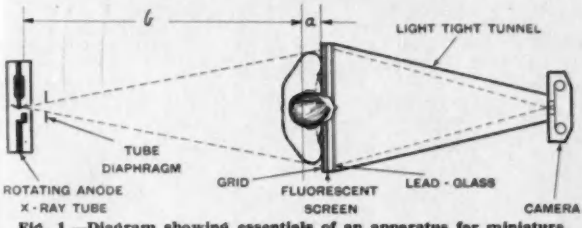

Fig. 1.—Diagram showing essentials of an apparatus for miniature film radiography.

secondary x-rays which are generated in the tissues from reaching the screen and impairing the quality of the fluorescent image. A light-tight tunnel is fitted to the fluorescent screen, having mounted at its far end an automatic camera fitted with a lens of large aperture and arranged to accommodate a sufficient length of standard 35 mm. film to enable some hundreds of separate exposures to be made without re-loading. Reduced photographic images of the fluorescent screen may thus be produced in large numbers. Eleven such images may be recorded on each foot of film, and with good organisation, as many as 200 such exposures may be made in an hour. The films are examined after projection to a convenient size, usually somewhat less than life size.

The success of miniature film radiography as a means of singling out patients having suspected chest abnormalities is dependent on the films being of very high quality, because foci of infection in their early stages may be of minute dimensions and result in only very slight changes in film density.

It is of interest next to consider in some detail the factors governing the quality of the final image on the miniature film. These can be conveniently discussed under three headings—the optimum exposure conditions for the radiography of a moving object—the factors affecting the fluorescent screen image—the factors governing the image on the miniature film.

4. OPTIMUM CONDITIONS FOR THE RADIOGRAPHY OF A MOVING OBJECT.

It can be shown[3] that the lack of sharpness—"unsharpness"— in a normal radiograph is the sum of the following three effects:

Unsharpness due to geometry of exposure conditions $= U_g$

Unsharpness due to movement $= U_m$

Unsharpness due to grain structure of the intensifying screens $= U_s$

The total unsharpness produced is

$$U = U_g + U_m + U_s \quad \cdot \quad \cdot \quad \cdot \quad (1)$$

(a) Geometrical Unsharpness (U_g).

U_g arises from the fact that the radiation is derived from a focal area of finite size causing the formation of a penumbral shadow around the image, the width of the shadow for a given tube-patient arrangement being proportional to the size of the focal spot and to the ratio of object/film to object/focus distances, *i.e.*, to $\frac{a}{b}$ in fig. 1.

We may write, therefore:

$$U_g = af \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad (2)$$

where a is a constant determined by the geometry of the arrangement being considered, and f is the size of the focal spot.

(b) Movement Unsharpness (U_m).

When radiographing the chest it is necessary to consider it as a moving object, since although the patient may be immobilised, the lung tissues, the details of which it is desired to record as sharply as possible, are in constant motion caused both by respiratory changes and by elastic rebound from movements imparted by the pulsations of the heart.

Cine-radiographic studies and other evidence[4] show a rate of movement of lung tissue varying from low values up to speeds of the order of 20 mm. per second. The best available evidence shows that the largest mass of lung tissue moves, in the case of an average patient, at a speed of about 5 mm. per second in a direction parallel to the plane of the film. It is apparent, therefore, that the radiographic image will be subject to an unsharp-

ness due to movement (U_m) which will be equal to the product of the speed of movement and the time of exposure. The time of exposure is inversely proportional to the size of the focal spot, since with an increase in the size of the focal area bombarded, the tube may be loaded more highly, and thus for a given film blackening the exposure time may be reduced. The exposure time is also inversely proportional to the intensifying factor k of the intensifying screens. With a modern rotating anode tube, which is the only type that will be considered here, the specific loading capacity, *i.e.*, the load per square mm. of target surface bombarded, is very nearly proportional to the focus width and we may therefore write:

$$Um = \frac{b}{f\,k} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where b is a constant, f the width of the focal spot, and k the intensifying factor of the screens.

(*c*) *Screen Unsharpness* (U_s).

With all types of fluorescent intensifying screens used in radiography, the amount of visible light produced is proportional, within small limits, to the grain size of the crystals of which the screen is composed. Screen unsharpness may therefore be written:

$$U_s = ck \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where c is a constant and k is the intensifying factor.

(*d*) *Total Unsharpness* (U).

The total unsharpness is thus equal to:

$$U = af + \frac{b}{fk} + ck \quad . \quad . \quad . \quad (5)$$

in which a, b and c are constants and f and k are the focus width and the screen intensifying factor respectively.

The sum of two or more numbers which are varied in such a manner that their product remains constant is lowest when the numbers are all equal.

It will be seen from equation (5) that the product of the three unsharpnesses is:

$$U_f \times U_m \times U_s = a.b.c. \quad . \quad . \quad (6)$$

and is thus a constant. It therefore follows, as Bouwers has pointed out, that for the value of U to be a minimum, the values of the various unsharpnesses should all be equal. Departures from strict equality do not necessarily introduce alterations of great magnitude, and small variations from the ideal condition can sometimes be justified by other technical factors. The principle outlined above must, however, always be considered when deciding on the technical conditions under which a radiograph will be made.

5. FACTORS AFFECTING THE FLUORESCENT SCREEN IMAGE.

In normal chest radiography it is customary to employ a focus/film distance of 5 feet in order to reduce distortional enlargement of the image to a reasonably small value.

Using tubes of the highest specific loading capacity available, it is difficult to obtain a sufficiently luminous screen to enable miniature films to be taken in exposure times which will permit a reasonably small movement unsharpness.

Experience indicates that the degree of

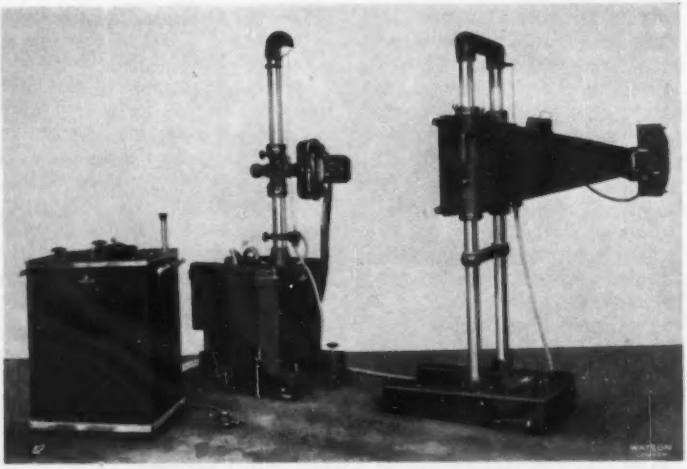

Fig. 2.—General view of the Watson apparatus for miniature film radiography, showing, left to right, control table, high tension transformer unit with X-ray tube, and screen and camera unit.

projective enlargement present on a fluorescent screen placed at a distance of 3 feet from the x-ray tube is not objectionable when once the radiologist responsible for diagnosis has become accustomed to the altered perspective.

Examination of the conditions indicated above suggests that the following technical factors should be employed :

1.	Focus/screen distance.	36 inches
2.	Rotating anode tube with focal spot size :	2 × 2 mm.
3.	Tube tension.	80 kV (peak) (57 kV. R.M.S.)
4.	Tube current.	400 mA. (mean)
5.	Exposure time.	0·1 second

In adult patients the lung tissues may be moving at about 5 mm. per second as far as 15 cm. away from the fluorescent screen. Considering this as a maximum, we get the following values for the unsharpness present.

$$U_g = 0{\cdot}4 \text{ mm.}$$
$$U_m = 0{\cdot}5 \text{ mm.}$$
$$U_s = 0{\cdot}6 \text{ mm.}$$

The screen unsharpness is not easily measured with accuracy, but the value of 0·6 mm. given, represents the mean of a number of different measurements made on the fastest type of screen available.

It will be seen that with the exposure factors suggested above, the "equality" condition is roughly fulfilled. The screen unsharpness cannot be reduced as far as is known without a reduction in the screen luminosity, which would necessitate either a longer exposure time (larger U_m) or a shorter focus/screen distance (larger U_g). Reduction of the latter is not practicable since with distances much shorter than 36 ins. the target angle of present-day rotating anode tubes (15°) does not permit of a cone of radiation sufficiently large to cover a 16 × 16 inch screen at shorter distances.

6. FACTORS GOVERNING THE IMAGE ON THE MINIATURE FILM.

The image produced on the fluorescent screen, already unsharp, tends to suffer further unsharpness as a result of the process of its reproduction on the miniature film. In the first place, points on the screen image are reproduced on the film as circles of confusion whose minimum dimensions are determined by the perfection of the lens system employed. In addition to this, the film has a quite appreciable graininess. The fastest available lenses suitable for producing a one inch square image on standard 35 mm. film have geometrical apertures of f/1·5. Lenses of this type differ somewhat in their freedom from disturbing aberrations, but a reasonable figure for the minimum circle of confusion averaged over the whole of the field is about 0·03 mm. The maximum unsharpness on the fluorescent screen as deduced above is of the order of 1·5 mm.; with a linear reduction of 16 : 1 this would reduce to about 0·1 mm. This is certainly quite large in comparison with the graininess even of the very fast emulsions used for miniature film radiography, and although further investigation in this direction will be interesting, it can be assumed that the image is not materially impaired by the characteristics of the film.

It will be noted, however, that the diffusion of the image on the film due to lens imperfections is approaching in magnitude the reduced value of unsharpness of the fluorescent screen image. Any considerable increase in the sharpness of this image brought about as a result of developments in screen manufacture or technical improvements in the production of x-ray tubes, will necessitate further review of the question of lens imperfections.

The exposure conditions given above can be employed if one of the special emulsions now provided by the leading film manufacturers is used. These films are, in general, developments of the high speed emulsions now available for normal photography and are specially sensitised for the spectral emission of the type of fluorescent screen employed.

The factors outlined above indicate the basis around which an apparatus for miniature film radiography should be designed. The remainder of this paper is devoted to a description of a complete apparatus for routine miniature film radiography. Standardised units of this type are now being produced by the Company in substantial quantities for use in the Government scheme for the combating of tuberculosis.

7. AN APPARATUS FOR MINIATURE FILM RADIOGRAPHY.

Fig. 2 shows the general arrangement of the apparatus. The control table shown in the left foreground controls all the operations necessary for the production of films in rapid succession, the movement of a single lever setting into motion the various electrical circuits, including the movement of the film in the camera. The apparatus has been so arranged that it may also be used for the production of full size radiographs, it being recognised that patients whose miniature film shows possible pathological changes should

always be radiographed on full size film and the diagnosis confirmed.

A consideration of the various conditions under which a miniature film radiographic unit might be used leads to the conclusion that a large proportion of the units needed will have to be sufficiently mobile to enable them to be dismantled and transported from one examination centre to another; there to be re-assembled by comparatively unskilled staff. With this end in view the whole equipment has been so designed that it may be dismantled into a number of elements, each of which may be transported without great difficulty. For the same reason, provision is also made for operation on any supply voltage likely to be encountered.

The various units of which the apparatus is comprised are described in some detail below.

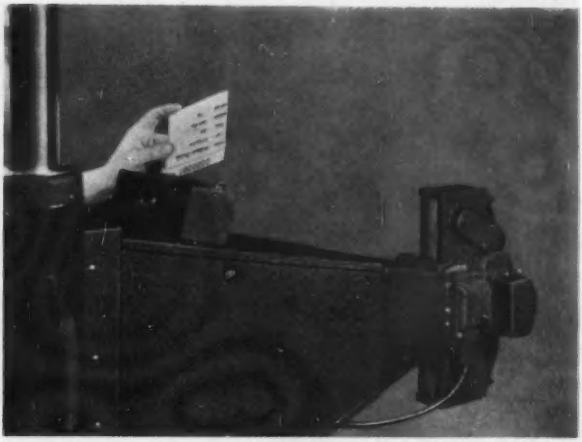

Fig. 4.—Camera tunnel showing patient's identification card being inserted into recess. Interlocking contacts prevent an exposure being made unless the card is correctly in place.

8. HIGH TENSION TRANSFORMER AND X-RAY TUBE.

The rotating anode x-ray tube is supported on a counterpoised vertical column, which is removably mounted on the top of the high tension transformer. The high voltage terminals of this transformer are connected to a four-valve, full-wave, bridge circuit, embodying oil-immersed, hot-cathode, high-vacuum rectifiers, the cathodes of which are energised from filament transformers all contained in the same tank as the high tension winding. A filament transformer for heating the cathode of the x-ray tube is also included.

The high voltage output from the four valve rectifier is delivered at tensions up to 100 kV. (peak) and currents up to 400 mA. (mean). The high voltage output terminates in two moulded sockets on the transformer top, into which are plugged flexible high tension cables, which connect to the x-ray tube, the whole arrangement being completely shockproof. The rectifying valves are so supported that they may be left in place during transport. The high tension transformer unit is mounted on a metal trolley so that it can be wheeled into position when being installed and assembled.

Fig. 3.—The optical sighting device for aligning the X-ray tube and fluorescent screen, in place in the diaphragm box.

The x-ray tube may be loaded at tensions up to 85 kV. (peak) at 400 mA. for periods of one-tenth of a second. It utilises a focal spot having dimensions which are effectively 2×2 millimetres and has sufficient thermal capacity to allow many hundreds of exposures to be made per day.

The aperture of the tube is fitted with a diaphragm box*, which limits the area of the beam to that of the fluorescent screen. This diaphragm box is arranged in such a manner that it will accommodate a removable optical sighting device* (fig. 3), with the aid of which the alignment of the

* Patents applied for (G.E.C. and Caldwell).

x-ray tube and the fluorescent screen may be rapidly checked. The sighting device enables rapid centring of the apparatus to be carried out when the unit is being installed and greatly facilitates readjustment after the unit has been dismantled and transported to another centre.

9. THE SCREENING AND CAMERA UNIT.

The fluorescent screen, lead-glass, tunnel and camera are supported on a counterbalanced, two-column stand which is in turn

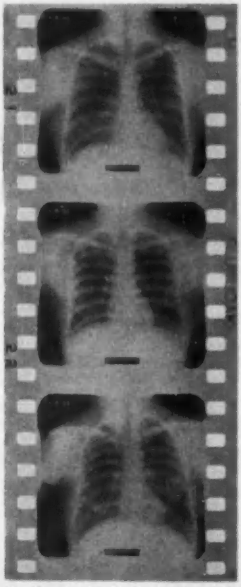

Fig. 5.—Reproduction (actual size) of a strip of film taken with the apparatus. The identification number, recorded in the centre of the lower edge of each frame, can just be discerned in the reproduction, but is quite clear in the original.

mounted on a mobile base. The base is fitted with a system of castors which with the aid of two levers can be so adjusted that, while installing, the stand can be wheeled in any direction. Once correctly positioned with respect to the x-ray tube, the base will move only in one direction, that is, parallel to the axis of the whole system.* This arrangement obviates the necessity for a floor track.

The base of the stand has been so designed that when a patient stands on it his feet will automatically be directed into a position which will ensure that his body is centred in relation to the fluorescent screen.

The camera tunnel can be quickly and easily attached to the fluorescent screen carriage and has a light-tight slide at the small end to accommodate the camera. A metal box on top of the tunnel contains a slide into which a card may be placed bearing an identification number and other particulars relating to the patient (fig. 4), thus enabling any film to be definitely identified after development. The image of the number, which is illuminated by a small lamp inside the box, is reflected by means of a system of mirrors so that it appears the correct way up in the centre of the lower edge of each frame* (see fig. 5).

Provision is made for recording an eight-figure number in characters $\frac{1}{8}$in. high, which, when printed on the film, can be read without the use of a magnifier, thus allowing identification of frames before placing a film strip in a projector.

The metal box incorporates a system of contacts so arranged that no exposure can be made unless the card is in place and its position correct with respect to the identification number.* The illuminating lamp for the card is connected in the circuit in such a manner that exposure is not possible should the lamp burn out. A relay system incorporated in the control table provides a circuit automatically energising the card illuminating lamp.

10. THE FLUORESCENT SCREEN AND SECONDARY RADIATION DIAPHRAGM.

The fluorescent screen is accommodated in a removable portion of the camera tunnel in order that it may be easily dismantled. The screen surface consists of crystals of zinc sulphide of a type giving an apple-green fluorescence. The range of fluorescent radiation from this screen extends from about 4,500 to 6,200 Ångstrom units, its maximum luminosity being in the region of 5,000 to 5,500 Ångstroms.

A screen of this type, activated by means of x-rays at 80 kV. peak, will yield about 0·1 candle power per square foot of screen surface per milliampere. The screen is covered with a sheet of lead-glass having a protective value equivalent to about 2 millimetres of lead, which reduces any radiation passing through the screen to a level at which it cannot cause fogging through the lens of the camera.

Provision is made for mounting closely adjacent to the fluorescent screen a "Lucidex" secondary radiation grid,* consisting of alternate sections of a ray-transparent material, and strips of lead foil. The lead strips block the passage of secondary radiation, which is generated at all points in the tissues of the

* Patents applied for (G.E.C. and Caldwell).

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patient as a result of the passage through him of the primary beam. This secondary radiation, if not cut off in this way, would cause diffuse

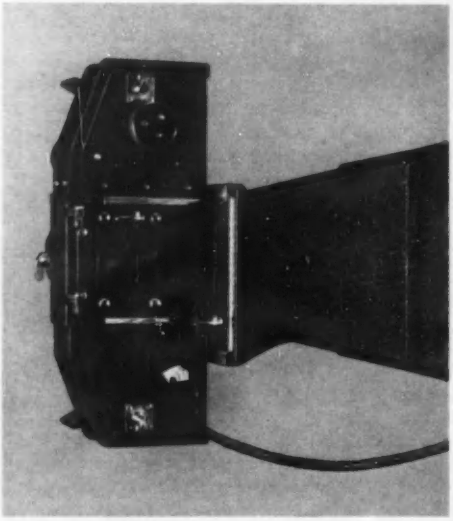

Fig. 6.—The electrically operated camera which is controlled automatically from the switchtable.

illumination of the screen surface, tending to reduce the contrasts present in the screen image. With the comparatively high kilovoltage which experience has shown is necessary for this type of radiography, the use of such a grid very materially improves the quality of the image.[5] The grid is so fine that its structure cannot be discerned on the film.

The upper edge of the fluorescent screen frame incorporates a chin rest and provision is made for the accommodation of cassettes to enable full size radiography to be carried out.

11. CONNECTION BETWEEN THE TUBE AND CAMERA STAND.

When a patient stands on the base of the camera and screening stand, the counterbalanced fluorescent screen and camera tunnel have to be adjusted to a height at which the patient's chest is correctly centred.

To facilitate rapid radiography, it is necessary that the x-ray tube is adjusted simultaneously. A simple and easily fitted flexible linking system has been devised for this purpose.* The moving carriage of the vertical column on which the x-ray tube is supported, is attached by means of a steel cable passing through a flexible housing to the moving carriage of the camera and screen stand in such a manner that, when the latter is moved up or down, the tube carriage moves simultaneously.

A special feature of the system is that means have been adopted to ensure that the steel cable is always under tension while its housing is always in compression. In this way "backlash" is avoided. This linkage is taken through a flexible metallic tube which protects it mechanically and serves also to house the electrical connections between the high tension transformer, the camera, and the card illuminating box.

12. THE CAMERA AND LENS.

The Camera has been designed from first principles as an integral part of the whole unit.* In view of the very large number of exposures which the camera is likely to have to make, it has been manufactured on more robust lines than is customary.

The general construction can be seen from figs. 6, 7 and 8. It consists of three main parts: the camera body, the exposed film cassette (top) and the unexposed magazine (bottom). The camera body is machined from a solid gun-metal casting, the gate through

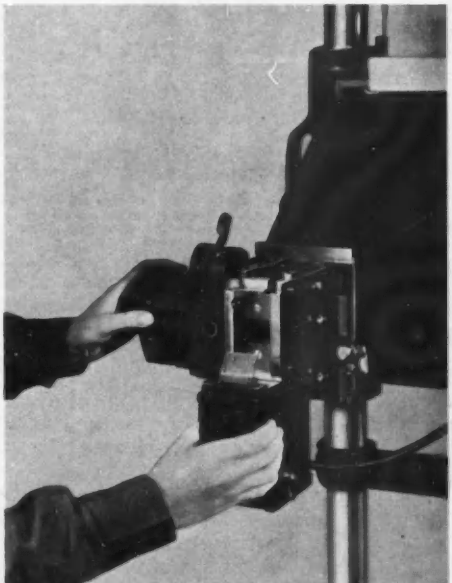

Fig. 7.—The camera with the gate open, exposed film cassette removed and the unexposed film cassette being placed in position.

* Patent applied for (G.E.C. and Caldwell).

which the film runs being machined from a steel block and highly polished.

The lens is rigidly attached to the gate of

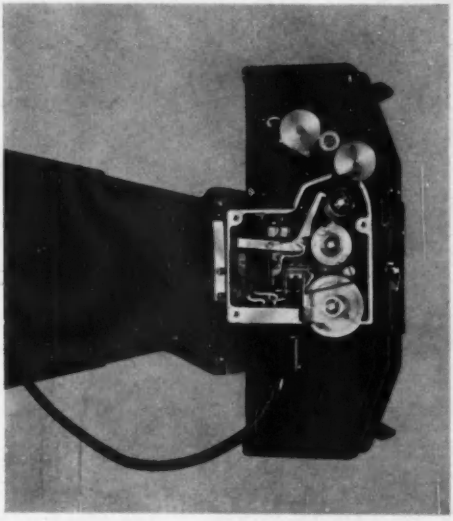

Fig. 8.—The camera with driving motor removed, showing contactor gear controlling automatic film spacing.

the camera in such a way that the exact relationship between the film and lens, necessary for accurate focusing, can be determined and then set permanently. With a lens of the aperture employed (f/1·5) a focusing error of 0·0015in. (0·038 mm.) would transform an ideally focused point image into a circle of confusion 1/1000in. in diameter (0·025 mm.) equal in its effect on the miniature film to the addition of about 25 per cent to the already existing unsharpness. The necessity for very accurate positioning of the lens and for a means of maintaining the film surface perfectly flat is apparent.

The camera is fitted with safety contacts and interlocks, which make it virtually impossible for an operator to make an exposure unless all parts of the apparatus are operating correctly. Some of the special features built into the camera are listed below :

(*a*) electrical drive, causing the film to move forward one frame immediately after each exposure.

(*b*) spacing switch which optionally allows the film to move forward two frames after each ten exposures so that the film may be cut up for filing.

(*c*) Manual movement of film by correct amount if desired.

(*d*) Electrical interlocking, ensuring that an exposure cannot be made unless film is in the gate—unless the take-up spool is taking up the slack film—the exposed film cassette is in place—the gate is closed—the patient's card has been illuminated—the camera is electrically connected.

(*e*) An automatically operated guillotine built into the exposed film cassette severs the film immediately the cassette is removed.

The lens employed has a focal length of 5 cm. and a geometrical aperture of f/1·5. It has been designed for this special purpose to yield a sufficiently flat field over an area of one inch square and utilises the minimum number of air-glass surfaces with which it is possible to obtain an image of suitable quality.

The loss of light by reflection at the various air-glass surfaces, which would reduce the incident light by a considerable amount, is largely eliminated by fluoride coating all the internal air-glass surfaces, thus greatly increasing the transmission of the lens.

13. THE CONTROL TABLE.

Fig. 9 shows the top of the control table. The procedure for taking a series of films is quite simple. The operator switches on all the control circuits by turning a combined mains switch and voltage compensator control. Adjustment of this control to a point where the needle of an indicating meter reads against a red line adjusts the incoming mains supply to a pre-determined value.

The kilovoltage at which a patient is to be radiographed is next selected. This may be judged either entirely by experience or by experience combined with a measurement of the patient's chest thickness. Generally this value will have been determined in advance and entered on the patient's identification card which he will bring with him into the x-ray room.

At any given centre where the unit is installed, the capacity of the mains supply will have been assessed and the maximum milliamperage value at which it is possible to work will have been determined and pre-set. The control is provided with an adjusting switch enabling all reasonable values of milliamperage to be obtained—values ranging from 100 to 400 mA may have to be used, depending on the mains supply available.

The exposure timer will already have been set to a value pre-determined after the milliamperage to be used has been decided. The

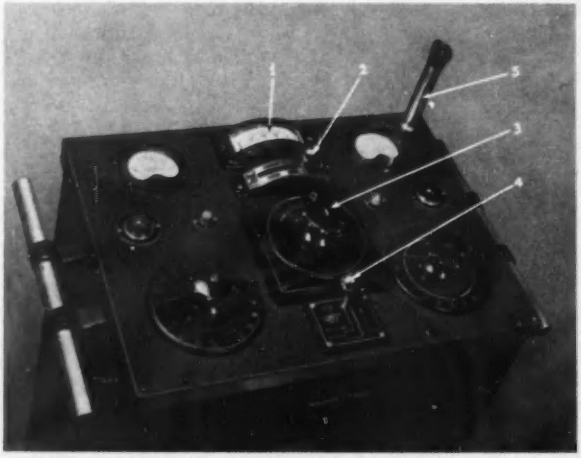

Fig. 9.—Top of control table showing (1) Milliamp-seconds meter with electrical reset (2) Milliamperage selector (3) Synchronous motor exposure timer (4) Exposure switch (5) Optical sighting device mounted in interlocking recess.

exposure switch seen in the front centre of the control (fig. 9) is then pulled forward to the "prepare" position, during which time the patient is instructed to inhale slowly and deeply, and to hold his breath (greater lung detail is shown when the lungs are well filled with air). When the patient is steady, the exposure lever is pulled sharply to the left to the "expose" position when the exposure will be made immediately. As the exposure lever is released, the camera driving motor will be automatically energised and the film moved on by one frame.

Whilst the exposure lever is held in the "prepare" position, the identification number is printed on the film, the illuminating lamp being automatically energised for a fixed period.

Pilot lamps on the control board light up intermittently and indicate the sequence of operations. Failure of any of these indicators to respond gives a clue to the nature of the difficulty.

The optical centring device shown in fig. 3 could conceivably be left in place during operation, in which case films would be spoiled. The control has therefore been so arranged that unless this centring device has been removed from the diaphragm box and plugged into a recess on the control panel exposures cannot be made.

To facilitate rapid assembly and connection of the apparatus when moved from one site to another, all electrical connections between the components are of the plug-in type. Multiple pin plugs and sockets have been developed for this purpose. These are shown in fig. 10, which gives a view of the rear of the control table with the protecting panels removed. In this view can also be seen various other components including the exposure contactor which is of a rapid acting type, making use of contacts of G.E.C. Heavy Alloy (British Patent No. 447567), which very materially improves its switching characteristics.

Fig. 11 is a view of the front of the control table, on which can be seen the auto-transformer, x-ray tube filament regulating resistances, exposure counter and various auxiliary relays.

The output of the apparatus (400 mA mean at tensions up to 100 kV peak) is sufficient to enable miniature films of the highest possible quality to be produced. Operating at 400 mA, full size radiographs of cases held back for further investigation can be made with exposure times of 0·05 seconds at a focus/film distance of 5 feet using intensifying screens of fine grain. With these exposure conditions values of the unsharpness present on the film are $U_g = 0{\cdot}2$ mm., $U_m = 0{\cdot}25$ mm., $U_s = 0{\cdot}25$ mm. This represents the highest degree of sharpness obtainable.

Experience with very large numbers of cases is needed before it is possible to determine with certainty how far the quality of a miniature film may depart from the highest attainable standard before it fails to reveal the earliest signs of disease. Experiments are proceeding using films of higher speed than those commercially available, with lenses of larger capacity and correspondingly lower energy inputs. The apparatus is also being operated under experimental conditions from portable petrol-electric generator sets in order to determine whether it is possible to take units of this type into localities where sufficiently large power supplies are not available.

14. CONCLUSION.

The development of miniature film radiography has been accelerated by the increase in tuberculosis which has become apparent during the war years. It is established that x-ray examination is the only known method of detecting tuberculosis before the appearance of symptoms, and that the only practicable method of application is by means of miniature film radiography.

Already arrangements are well advanced for the periodic examination of selected sections of the community in addition to the Fighting Services, and there is little doubt that eventually the whole of the population will be included. It is the considered opinion of some of the leading authorities that, in conjunction with preventive measures, miniature film radiography will in course of time result in the eradication of pulmonary tuberculosis as effectively as vaccination has eradicated smallpox.

To what extent the method may be applied in other directions has yet to be established, but it seems reasonable to suppose that in the industrial sphere it will prove to be an economical method of radiographing suitable articles manufactured in large quantities.

REFERENCES.

1. Medical Research Council—Report of the Committee on Tuberculosis in War Time. Special Report Series No. 246, H.M. Stationery Office.
2. Bleyer, J. M., On The Bleyer Photo-Fluoroscope. *Elec. Eng. (N.Y.)* 22. 10. July 1 (1896).
3. A. Bouwers & W. J. Oosterkamp. Die Unschärfe einer Roentgenaufnahme Forts a. d. Geb. d. Roentgenstr. 54. 67. 1936.
4. Chamberlain, W. E., & Dock, W. Study of the Heart Action with the Roentgen Cinematograph. *Radiology* 7. 185/189. 1926.
5. Clarke, K. C., Mather Cordiner, G. R., & Ellman, P. Experiments in X-ray Screen Photography with Direct Control Radiography. *Brit. J. Radiol.* XIV, p. 54/62, February 1941.
6. The Rationale of Chest Radiography. Watson & Sons (Electro-Medical), Limited.

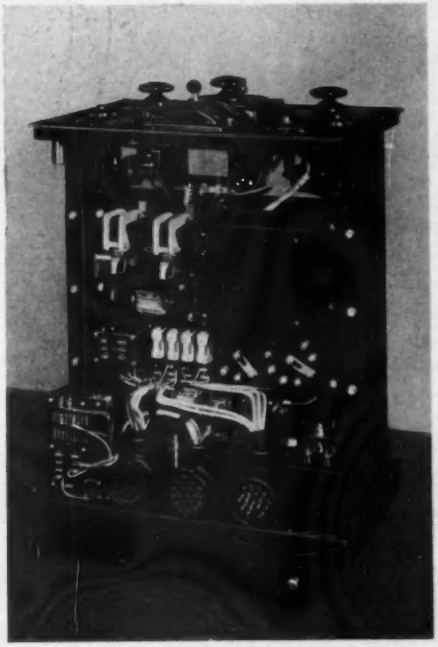

Fig. 10.—Rear of control table with panels removed. Note multiple plugs and sockets for interconnection and exposure contactor (top left) with G.E.C. heavy alloy contacts.

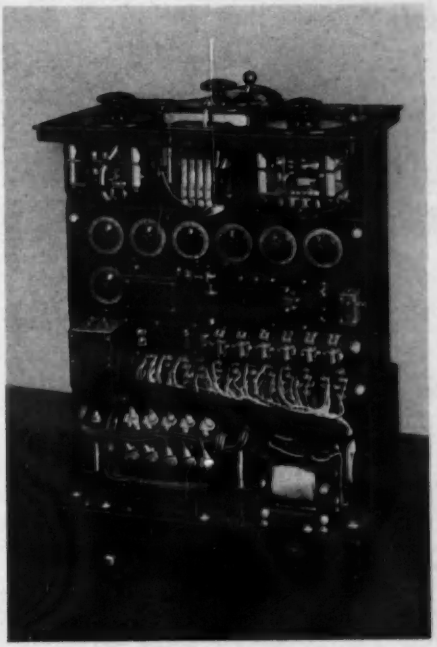

Fig. 11.—Front of control table with panels removed, showing main auto-transformer, X-ray tube filament adjusting resistances and auxiliary relays.

Gold Milling Plant for South Banket Areas Limited, West Africa.

By WILLIAM BULLOCK, Assoc. Inst. M.M., A.I.Q.M.,
Mining Department, Fraser & Chalmers Engineering Works.

INTRODUCTORY.

THE installation which is the subject of this article forms a complete gold milling plant, comprising both the treatment and electrical equipment supplied to the South Banket Areas for their Banket Reef Mine, and is capable of treating 15,000 tons of ore a month.

Some of the samples of ore submitted for testing carried as much as 12 dwt. of gold per ton, but the average was in the neighbourhood of 5 dwt. per ton and contained only a small quantity of sulphides. The tests performed indicated that a straight grinding to approximately 100 mesh I.M.M. would give a satisfactory extraction of the metal by separation of the coarser grains on strakes, followed by cyanidation.

The ore is mined from the Banket Reef, which runs through the property, and is hoisted from three shafts at Effuenta, and North and South Tamsoo respectively, being brought to the main ore bin by means of ropeways (fig. 4). It is the intention of the Company to sink a main vertical shaft in the locality of the mill which will eventually supply the bulk of the ore to be treated. A general view of the mill site is shown in fig. 1.

The requisite power plant was supplied by The General Electric Co. Ltd., and includes generators and switchgear together with the various outdoor substations and their equipment. In addition, there were supplied all the necessary transmission links and cabling as well as a large number of motors of various types employed in the treatment processes.

Fig. 1.—General view of the mill site showing erection in progress.

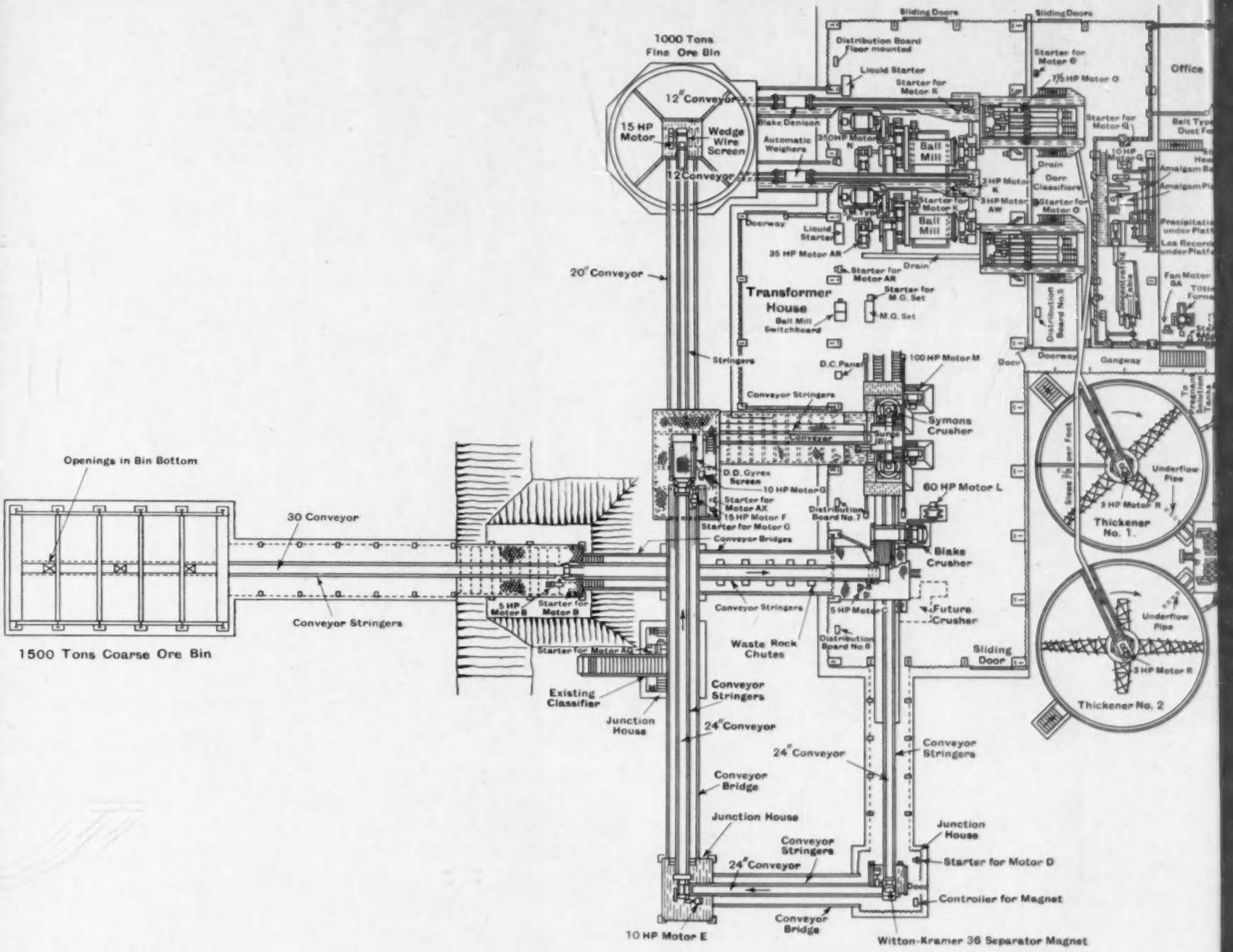

Fig. 2.—General plan of the gold treatment plant.

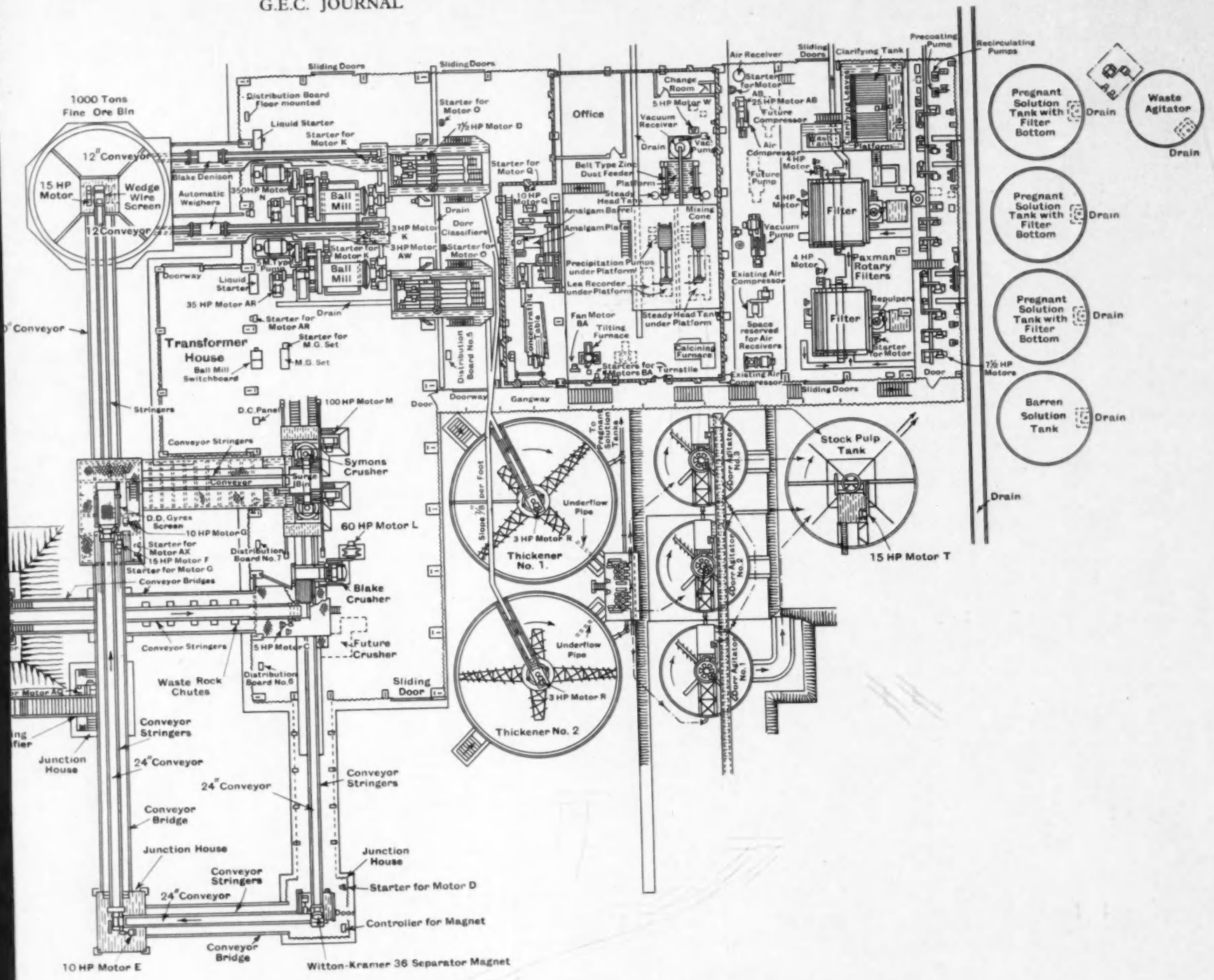

Fig. 2.—General plan of the gold treatment plant.

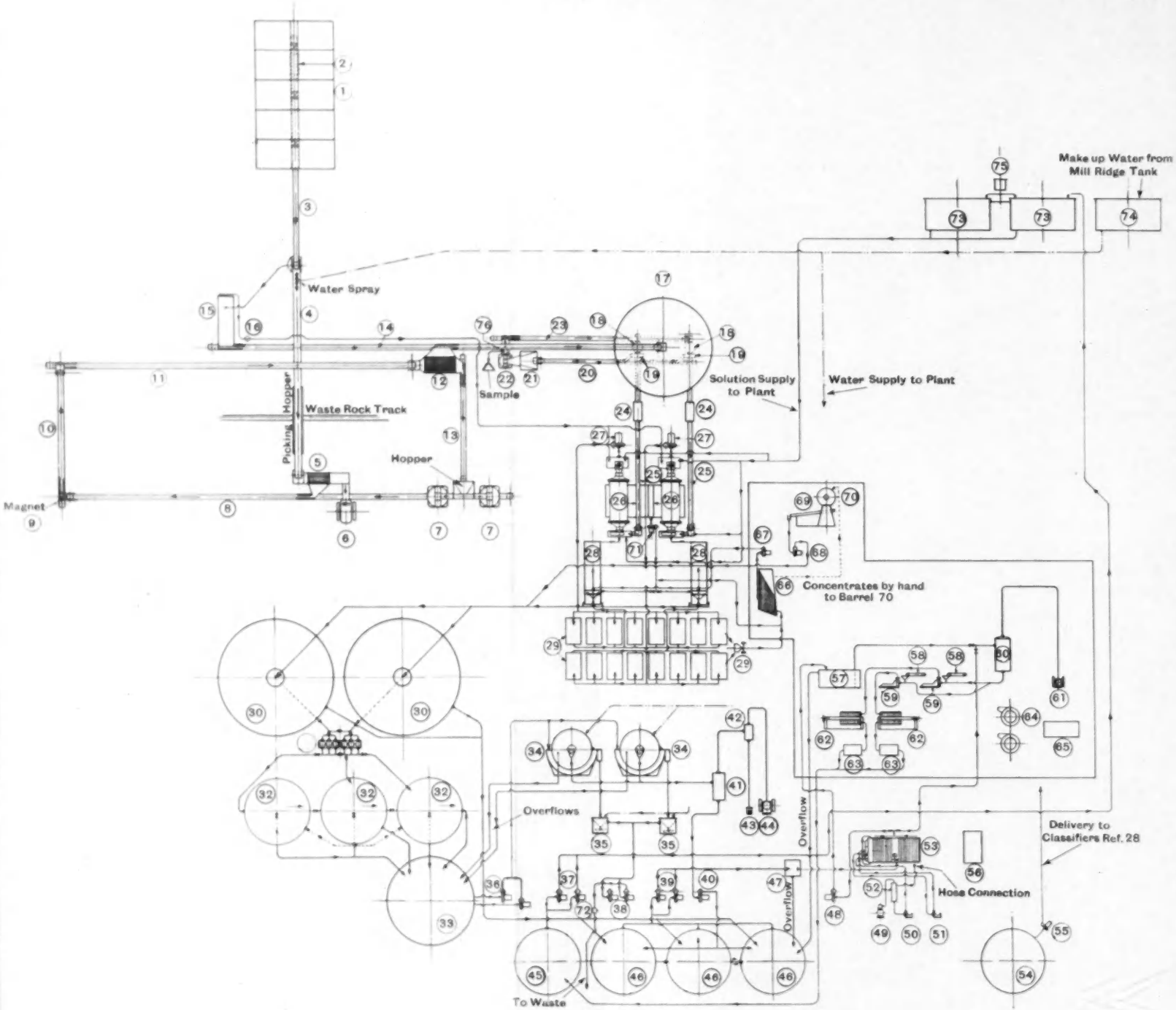

Fig. 3.—Flow Sheet.

A detailed description of this equipment is given later under its appropriate heading.

The treatment plant was supplied by Fraser & Chalmers Engineering Works,

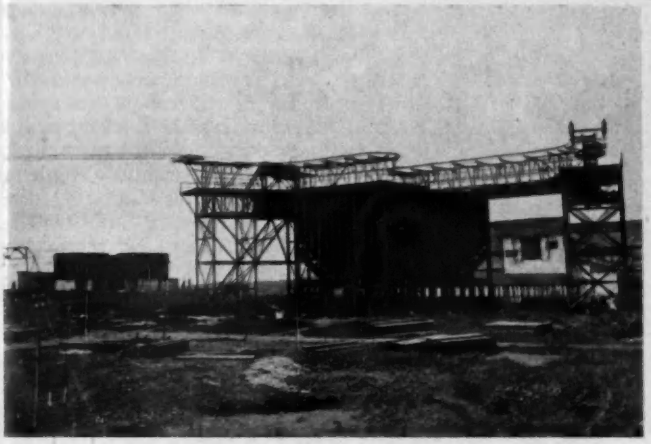

Fig. 4.—Ropeway terminal and main ore bin.

and the complete installation, including all steel buildings and bins, having been erected by their engineers, is now in operation.

TREATMENT OF THE ORE.

The layout of the plant as finally approved by the consulting engineers for South Banket Areas Ltd. (fig. 2) is briefly described below.

Reference to the flow sheet (fig. 3) will indicate the progress of the ore through the plant, while the following description will serve to explain the different stages necessary to recover the gold.

The main ore bin of 1,500 tons capacity, see fig. 3 (1) and fig. 4, is supplied by three ropeways which bring the ore from separate mine shafts during the day shift, and from this bin a regular supply of ore is drawn and passes to a picking belt (4) where waste material is discarded.

The ore is next crushed in a primary Blake crusher (6) and then reduced to ½in. in Symons cone crushers (7), and fig. 5, operating in a closed circuit with a Gyrex screen (12), the undersize from which passes to the 1,000-ton circular mill bin (17), and fig. 6, the whole operation being carried out in one shift. From the mill bin to the discard of tailings the operation is continuous day and night.

As the ore is withdrawn from the mill bin a sample is taken automatically, and at definite intervals, while the balance passes over continuous weighing machines (24) and is ground to −100 mesh in two 6ft. × 13ft. ball mills (26), and fig. 7, where water or cyanide solution is added.

The pulp issuing from the mills is further diluted and then pumped over strakes (29) where the first concentration takes place; the coarse gold and heavy sulphides being retained on the surface of the strakes, while the overflow gravitates to Dorr classifiers (28), which separate any coarse particles which are returned to the grinding circuit, while the fines or overflow product are laundered to two 45ft. × 10ft. thickeners (30). In these thickeners the solution carrying only a small percentage of gold is separated from the settled pulp, the former gravitating to the pregnant solution tanks (46) and the latter to the agitators (32). Additional cyanide is added,

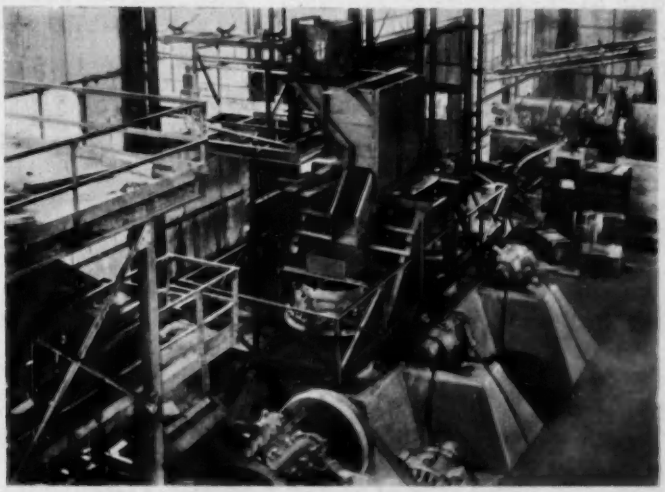

Fig. 5.—Crusher house with ball mills and Symons cones in course of erection.

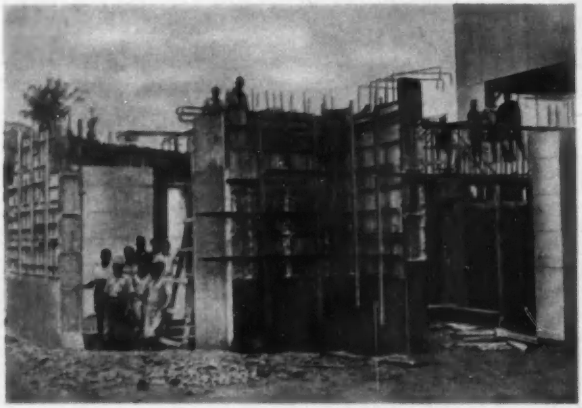

Fig. 6.—Reinforced concrete foundations for 1,000-ton circular mill bin.

if required, in these agitators where the pulp remains until the rest of the gold in the pulp is dissolved by the solution.

The pulp is then transferred to a stock pulp tank or reservoir (33), whence it is pumped to two 14ft. × 16ft. Paxman filters (34), and fig. 8, the pregnant solution being drawn through the filters and discharged to the appropriate solution tanks, while the cake, or residue, after mixing with water is pumped to waste.

The pregnant solution from the tank (46) is then pumped to a clarifying tank (53), furnished with filter leaves upon which any solids in suspension are intercepted, the clear solution being extracted by a vacuum pump (61) into a receiver (60) where it is de-aerated and, after having a small amount of zinc dust added (58) in order to precipitate the gold from the solution, is pumped through two presses (62) which retain the precious metal, while the clear or barren solution returns to the circuit tank (45) for re-use in the plant.

Periodically the gold is removed from the presses, dried and the necessary fluxes added, and then melted in the crucible furnaces (64); the fine bullion being then poured into moulds.

To return to the strakes (29) upon which the coarse gold and sulphides have been deposited: any of the strakes can be independently cut out from the circuit and the deposit upon them collected and transferred to a concentrating table, upon which a final concentration is effected. The coarse, or richer, portion is charged into an amalgamating barrel, to which a small amount of mercury is added, and then ground, the mercury forming an amalgam with the gold. The contents of the barrel are then discharged on to an inclined silvered copper plate (69) upon which the amalgam is deposited; the fines, now practically free from gold, overflow this plate and are pumped to the thickeners (30) for circulation through the main plant for the recovery of any values which may remain after dissolution by the cyanide solution.

The gold amalgam is scraped from the plate (69) and charged into a retort, the mercury being volatilized and then recovered, while the gold sponge is melted down in one of the furnaces (64) for fine bullion.

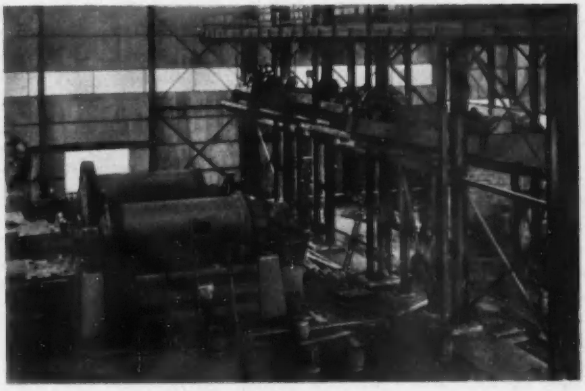

Fig. 7.—Ball mill and classifiers.

In operation, the plant has given a recovery up to 98 per cent of the precious metal contained in the ore.

ELECTRICAL EQUIPMENT.

General.

The electrical equipment comprises the main power plant, the main high tension switchboard and complete outdoor substation, the overhead high voltage transmission lines to Mill Ridge Main Substation and to Tamsoo North "A" and "B" and Effuenta North Substations, and their complete equipment, including all cables required.

From Mill Ridge a supply is taken by underground cable to the Mill Substation proper, for which all the necessary electrical

gear was supplied, as well as a large number of motors of various types required for the actual recovery processes.

Power House Equipment.

The power plant in the main Tamsoo Power House (fig. 9) consists of 3—725 kW alternators direct coupled to 1,000/1,100 h.p. Crossley Premier oil engines running at 214 r.p.m. Current is generated at 2·2 kV and is brought out to the main 14-panel truck cubicle switchboard whence it is fed to the low tension side of 2—1,500 kVA transformers which step it up to 11 kV for transmission to the various substations. Two 150 kVA auxiliary step-down transformers furnish a low tension supply at 220 volts for the three 40 h.p. motors driving blowers for the supercharging of the oil engines and for the four 12 h.p. squirrel cage pump motors at the hot well.

The equipment of the outdoor substation includes a current limiting reactor for tying in with the existing supply, and the usual air-break isolating switches on the high tension side, all switching being carried out on the low voltage side. Owing to the prevalence of thunderstorms lightning arresters are installed at each end of the various transmission lines in all cases.

Mill Ridge Substation.

Mill Ridge Substation is situated at a distance of approximately three-quarters of a mile from the Power House and receives its high tension supply at 11 kV direct by overhead transmission line. Two 1,250 kVA transformers serve to step down the current to 2·2 kV whence it is distributed by the main high tension switchboard to the incoming 2·2 kV board at the mill substation, and also to an auxiliary 150 kVA transformer which provides a low tension supply at 440 volts for various purposes. The equipment of the outdoor substation is generally similar to that at the Power Station and includes high tension air-break isolators and lightning arresters.

Fig. 8.—Vacuum filters

Mill Equipment.

Mill Substation.

The Mill Substation provides power for the various mill motors which may conveniently be divided into two groups: the low voltage machines operating at 440 volts and the high voltage machines at 2·2 kV.

Distribution to Low Voltage Motors.

The incoming power which is brought in by underground cable is taken direct to the main 6-panel 2·2 kV switchboard from which two feeders carry a supply to the two 400 kVA step-down transformers which provide current at 440 volts for the low voltage machines. From the low tension board in the transformer house current is fed to 8 distribution boards situated in various parts of the mill each of which, in turn, supplies a number of small motors varying from fractional ratings up to about 50 h.p., which are employed for the crushing, screening and milling plant. There are, in all, 66 of these motors comprising both squirrel cage and slipring machines all of the totally enclosed, fan cooled, dust proof type, of an aggregate horse power of approximately 650. Provision is made on the boards for future extensions.

Distribution to High Voltage Machines.

As already mentioned, the high voltage machines operate from the 2·2 kV supply, which is taken from two panels on the high tension switchboard in the transformer house direct to the Ball Mill switchboard. From here it is distributed to the various machines described below.

The two ball mills are each driven by a 350 h.p. synchronous induction motor · running at 750 r.p.m. and started up by means of a motor-operated liquid starter. The circuit breakers on the main switchboard controlling the supply to the stators of the machines can,

in an emergency, be tripped by means of push-buttons mounted in proximity to the motors.

From the second panel of the switchboard a supply is provided for the 60 h.p. slipring induction motor driving the Blake Crusher and for the two 100 h.p. slipring machines driving the Symons crushers. The former is equipped with an oil-immersed rotor starter, the latter with manually operated liquid starters. These machines also are provided with emergency push-button control.

From the 3-panel Blake Crusher switchboard a feeder runs to the 60 h.p. slipring motor driving the vacuum pump. This machine is provided with an oil-immersed rotor starter.

A D.C. supply at 110 volts is provided for the 2½ kW 36in. Witton-Kramer magnetic separator. This is derived from a motor-generator set consisting of a 16 h.p. squirrel cage motor supplied from the low tension board at 440 volts A.C. direct coupled to a 10 kW D.C. generator. The control gear includes a star-delta starter for the driving motor and a D.C. control panel. The magnetic separator is operated by a drum type controller.

Tamsoo North and Effuenta Substations.

Power at 11 kV is carried by overhead line to Tamsoo North "A" Substation, a distance of approximately 1,000 yards. The equipment of this substation comprises a lightning arrester, outdoor isolating links and 2—250 kVA 11/2·2 kV stepdown transformers. From the high tension side a tie line is taken to Tamsoo North "B," which is situated on the main transmission line to Effuenta North and which is equipped only with the necessary isolating links and lightning arrester.

Effuenta North Substation is situated about a mile from the Power Station and its equipment is generally similar to that installed at Tamsoo North "A." In both cases provision is made for a 440 volt supply to existing low tension switchboards.

In conclusion, the author desires to acknowledge his indebtedness to The South Banket Areas Ltd. for their courtesy in granting permission for the publication of the foregoing information and photographs.

Fig. 9.—The three 725 kW engine driven alternator sets in course of erection in the main Tamsoo power house.

Developments in the Design of Heavy Duty Metalclad Switchgear.

By C. J. O. GARRARD, M.Sc., A.M.I.E.E. and A. H. WORLOCK,
Engineering Works.

INTRODUCTORY.

THE latest improvements in the design of G.E.C. heavy duty metalclad switchgear, although they have resulted in better adaptation to the difficult conditions arising out of the war, were, in the main, not the outcome of these conditions, but steps in a logical process of development which has proceeded without any pronounced change of direction for the last 15 years.

The original designs, produced in 1928, made use of double break circuit breakers which were isolated from the busbars by being lowered vertically. These features are retained in the latest models, as they offer advantages in respect of reliability, compactness, and ease of maintenance and inspection which are shared in equal measure by no other type of construction.

Notable improvements which have been made during the last few years are the introduction of condenser bushing busbars, and the application of side-blast arc control pots to the circuit breakers.

The principal developments which are described in this article are the production of a low oil content type of double break circuit breaker, the extension of the use of condenser bushings for the main connections, the substitution of fabricated steel for cast metal chambers in the busbar structure and the complete enclosure of the gear in serviceable steel covers with roller shutter doors; in addition there are many improvements in detail. Typical examples are shown in figs. 1, 2 and 3.

The resulting gear combines the advantages of an extremely reliable and easily accessible circuit-breaker, the contacts of which may be inspected without removing the oil from its tank or breaking oil tight joints, with those of a design requiring comparatively little oil. The absence of horizontal creepage surfaces in the busbar spout insulators eliminates a possible source of trouble due to tracking following the accumulation of dirt and moisture, while the plug-in isolating contacts enable oil immersed isolators to be avoided. The use of steel enclosures throughout and the complete enclosure of the gear give an added security against the risk of fire which is already minimised by the reduction of the amount of oil and compound.

Fig. 1.—Four panel 11 kV single busbar switchboard, showing enclosure and roller shutters. One shutter is raised to show the circuit breaker in the service position.

RANGE OF DESIGNS.

The new line of switchgear includes units suitable for voltages from 6·6 kV to 33 kV with breaking capacities from 500 MVA to 1,500 MVA, and current ratings in accordance with Table 1.

TABLE 1.

kV	MVA	Current rating in amperes				
6.6	500	—	800	1200	2000	—
11	500	—	800	1200	2000	—
11	750	—	800	1200	2000	3000
22	750	400	800	1200	—	—
22	1000	—	800	1200	1600	—
33	500	400	800	—	—	—
33	750	400	800	1200	—	—
33	1000	400	800	1200	—	—
33	1500	—	—	1200	—	—

Single busbar, double busbar and ring busbar (mesh connected) units are available. In double busbar equipments, busbar selection is provided by transferring the circuit breaker itself from one set of busbars to the other. The circuit breakers may be provided with electrical solenoid, spring or pneumatic operating gear.

GENERAL DESCRIPTION OF THE UNITS.

A cross section of a typical unit is shown in fig. 4. The main supports are in the form of welded steel pedestals, which, besides carrying the busbar structure and the circuit breaker hoist gear, serve as divisions between adjacent units.

Each busbar consists of a series of condenser bushings, joined end to end by connecting clamps housed in oil or compound filled chambers; these chambers are extended downwards to accommodate the flexible connections to the female plug contacts by which the breaker is isolated. The plug contacts are supported by porcelain insulators cemented into flanges bolted to the lower ends of the chambers. Similar spouts and chambers are provided for the conductors leading to the cable boxes, condenser bushings again being used for the main connections.

The chambers are bolted together to form a rigid structure which ties the upper extremities of the supporting pedestals, and carries the current transformers; these are of the ring type and are slipped over condenser bushings provided for this purpose. The current transformers and secondaries are

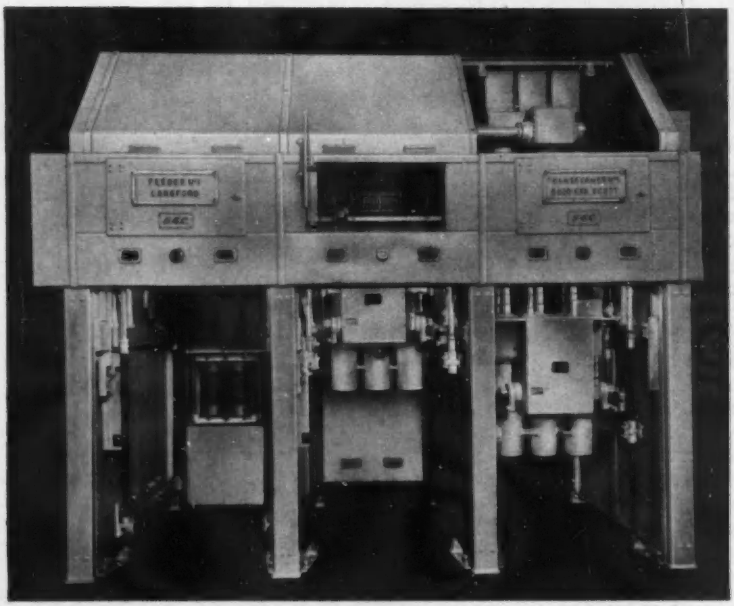

Fig. 2.—Part of a 33 kV duplicate busbar switchboard. The roller shutters are open and show, from left to right, a voltage transformer in the isolated position with its tank lowered, a circuit breaker in the service position and a circuit breaker in the isolated position.

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KEY.

(1) Breaker transport bogie.
(2) Pedestals.
(3) Circuit breaker.
(4) Arc control pots.
(5) Circuit breaker operating mechanism.
(6) Circuit breaker hoist gear control panel.
(7) Roller shutter.
(8) Shutters on isolating contact spout insulators.
(9) Panel containing auxiliary switches, local control gear, etc.
(10) Circuit breaker auxiliary contacts.
(11) Circuit breaker bushings.
(12) Spout insulators.
(13) Busbar connections.
(14) Busbar joint chambers.
(15) Steel covers.
(16) Busbar condenser bushings.
(17) Connection to current transformer primary conductor.
(18) Current transformer connection chambers.
(19) Circuit breaker hoist gear.
(20) Current transformer cores and secondaries.
(21) Cable box.
(22) Circuit breaker vent.
(23) Voltage transformer fuse and limiting resistance.
(24) Multicore terminal box.
(25) Voltage transformer.
(26) Voltage transformer hoist gear.

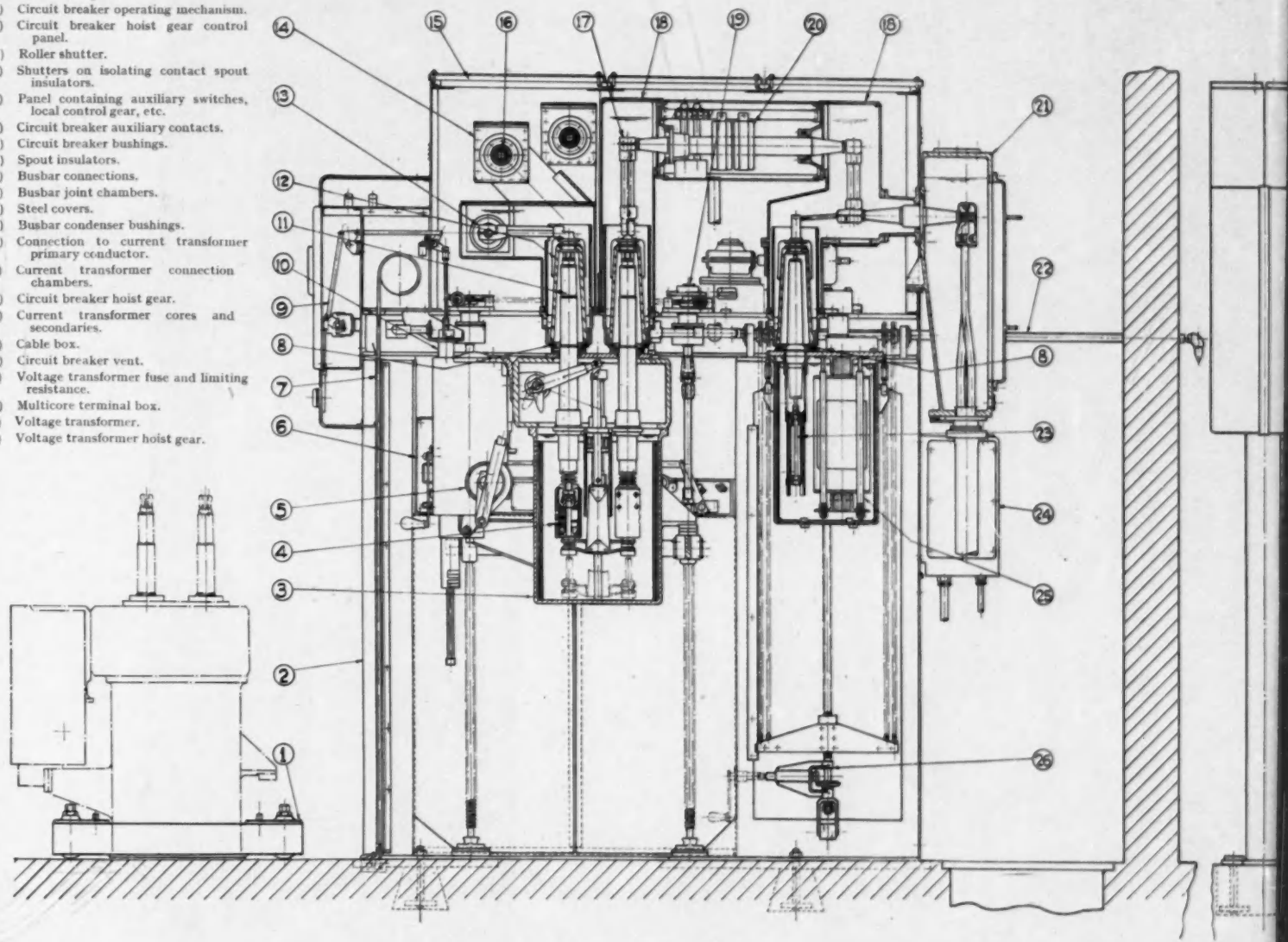
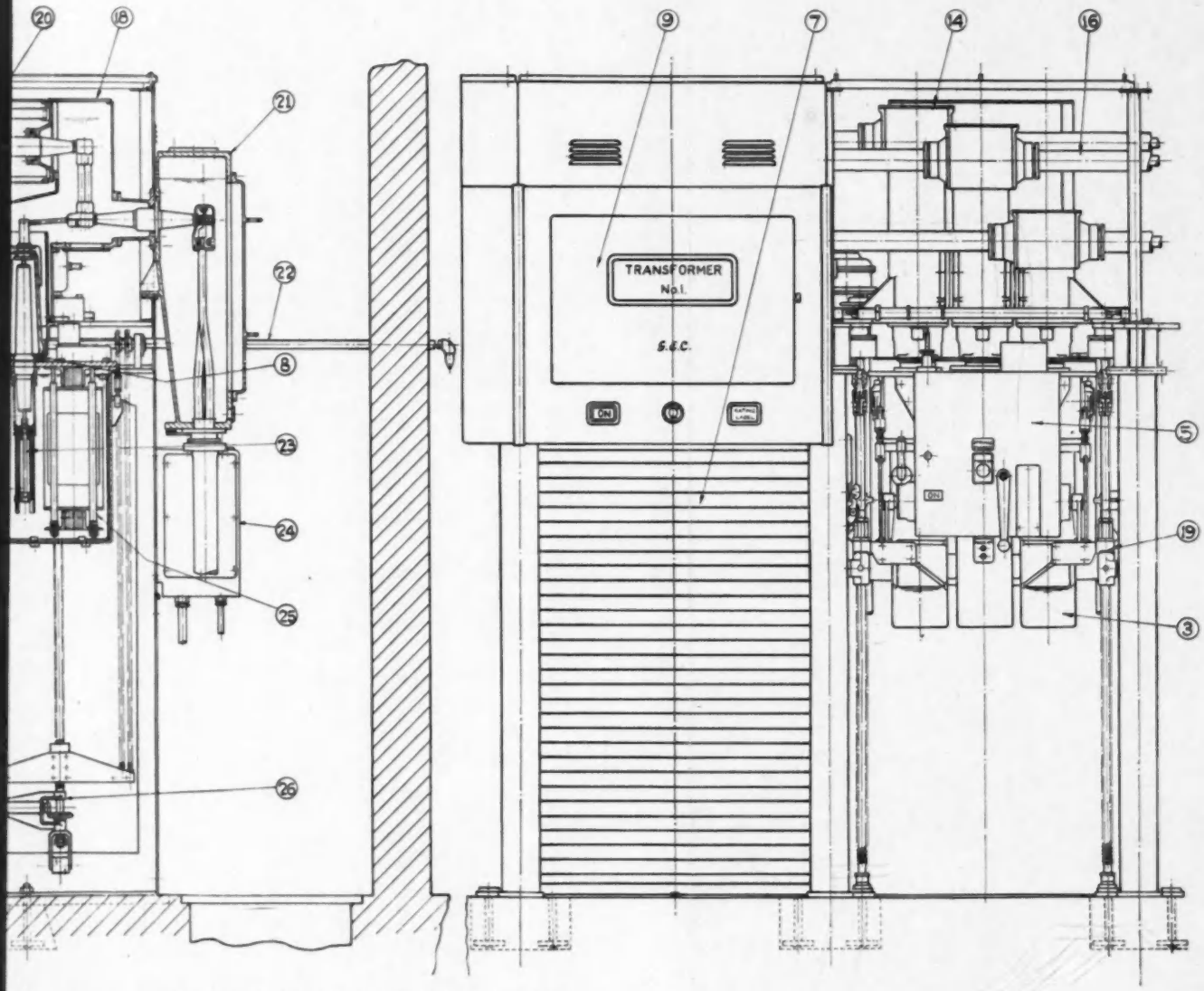


Fig. 4.—Cross section of a single busbar 33 kV unit complete with circuit breaker and current and voltage transf



33 kV unit complete with circuit breaker and current and voltage transformers.

therefore accessible at any time for inspection and may be removed by detaching the bushing from the circumjacent connection boxes.

The cable boxes are situated at the rear of the units at such a height that the cables may be made off conveniently.

The pedestals carry hoist gear for the circuit breaker and, in the case of 22 kV and 33 kV units, for the voltage transformer, where this is provided. Both breaker and transformer have terminal bushings which engage with the vertical spouts mentioned above. In 11 kV units the voltage transformers are carried above the current transformers, and in all cases the voltage transformer is connected to the side of the current transformers remote from the circuit breaker so that it is in the protected zone.

The top and rear of each unit are enclosed by easily removable steel covers, while normal access for inspection and maintenance is provided by means of a steel roller blind shutter which encloses the front of the unit; this has the advantage over the usual doors that when it is open it does not obstruct the gangway in front of the switchboard.

DISPOSITION OF UNITS.

Several alternative dispositions of the units are possible in order to suit the requirements of different situations. The adoption of condenser bushings for all the main busbars and connections enables portions of the switchgear to be isolated from one another by means of fireproof walls with comparatively little trouble, as the only modification to the standard unit which is necessary is slightly to increase the length of certain bushings so that they may pass through the dividing walls.

Several typical arrangements are shown in fig. 5.

Fig. 5(a) is a variation of the basic unit shown in fig. 4, the cable boxes being separated from the remainder of the gear by a fire wall (fig. 6). In the event of damage to the gear itself, the cables remain protected, and the necessity, which may otherwise arise, of jointing a new section to the cable may be avoided.

Fig. 5(b) illustrates the 11 kV equivalent of the arrangement of fig. 4; double busbar transfer breaker equipments for 11 and 33 kV are shown by figs. 5(c) and 5(d), while fig. 5(e) shows a 33 kV unit suitable for the mesh connection of the breakers illustrated in fig. 5(e4).

In the 22 kV and 33 kV units, access to the voltage transformers may be obtained either from a gangway behind the units (as in fig. 4) or from the front, underneath the circuit breaker, in which case the bushings of the voltage transformer may be removed so that it may be run out under the breaker while the latter is in service.

DETAILS OF CONSTRUCTION.

Circuit Breakers.

The circuit breaker is the heart of the unit; upon its performance depends the reliability and effectiveness of the gear, while its dimensions govern those of the whole installation. The circuit breakers contained in the new units are of a design which, although it retains those features of simplicity and ease of maintenance which are characteristic of the double break construction, yet contains a quantity of oil which is comparable with that used in single break breakers of similar capacity. Access to the arc control pots and contacts is obtained by simply lowering the tank, together with the oil which it contains, by means of the self-contained circuit breaker hoist gear.

Fig. 3.—A seven panel 33 kV switchboard, showing fire walls on either side of the busbar sectionalising breaker.

Typical examples of the range of breakers are shown in figs. 7(a) and 7(b).

The top plate consists of a strongly ribbed box construction which provides a substantial support for the bushings on which the contacts are carried, and constitutes an expansion chamber for the products of arcing which are emitted from the breaker itself. It also provides accommodation for the levers by which the moving contacts are actuated and supports the guides and dashpots for the moving contacts. Further, it is extended forward as indicated by figs. 7 and 9 to form a housing for the operating mechanism which may be of the solenoid or spring type.

At their lower ends the condenser bushings support the arc control pots and, on their upper ends, carry the male contacts which provide the connections with the busbars and cables. The bushings themselves are supported both at the top and bottom of the top plate, and are thus held very rigidly against the forces produced by the short circuit current and by the reaction of the gases discharged from the vents of the arc control pots.

Each phase of the breaker is contained in a separate tank, these tanks being welded to a common flange bolted to the top plate; metal-to-metal joints are used throughout.

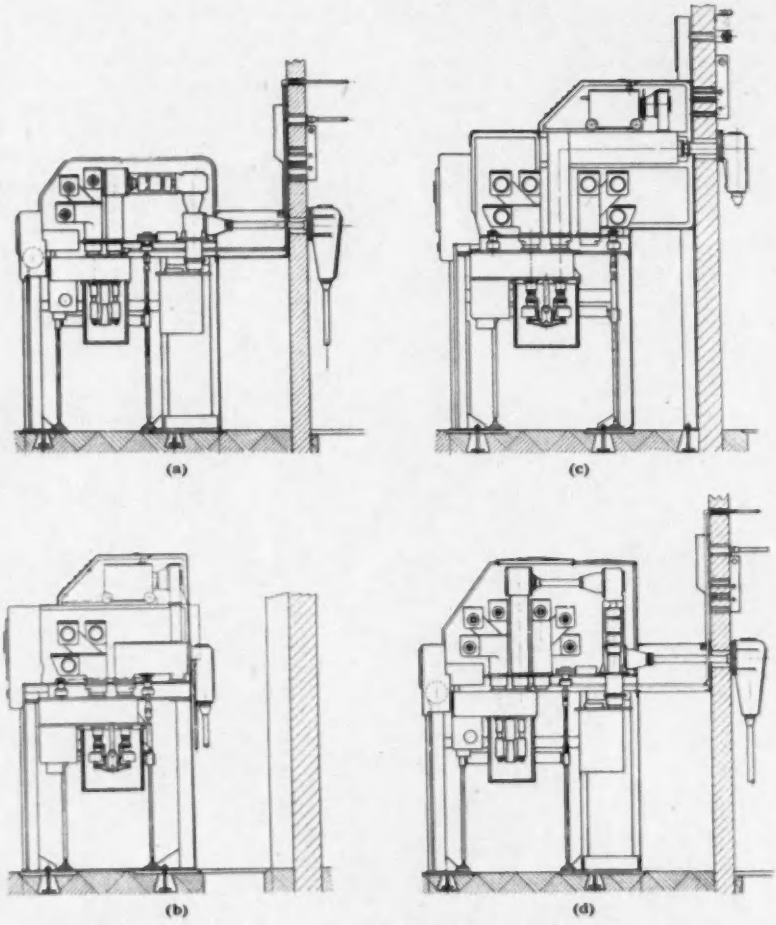


Fig. 5.—(a) Cross section of a 33 kV single busbar unit with cables separated from the unit by a fireproof wall. (b) Typical 11 kV single busbar unit. (c) Typical 11 kV double busbar unit, with cables protected by fireproof wall. (d) Typical 33 kV double busbar unit with cables protected by fireproof wall.

By careful design of the current carrying parts and arc control pots it has been possible to reduce their size, and, by avoiding sharp corners, to reduce the clearance between live metal and the earthed tank. Thus it became possible to reduce the size of the tank itself and with it the quantity of oil. The tanks are provided with linings of synthetic varnish impregnated paper or fabric, which is in turn protected from the blast of the arc control pots by means of supplementary laminated wooden linings.

The arc control pots fitted to the whole range of circuit breakers are of the side blast type in which the arc is extinguished by a blast of oil and gas produced by the action of the arc itself. Two constructions are used depending upon the voltage. For voltages up to 22 kV the pots consist of a cylindrical casting in the interior of which are accommodated the fixed arc contacts (fig. 8(a)). This terminates at its lower extremity in a flange to which is bolted a stack of plates of horn fibre so shaped as to form a series of internal cavities and lateral vents, to the effective design of which is due the action of the pot. Steel bolts are used to attach these plates to the upper flange, their heads being insulated by a covering of panilax resin bonded fabric, which combines great strength and resilience with good insulating properties.

For 33 kV service voltage it becomes desirable to avoid the introduction of metal parts into the lower extremities of the arc control pots. Accordingly a construction is adopted consisting of an outer cylinder of synthetic varnish bonded fabric which extends upwards and surrounds the fixed arcing contacts (fig. 8(b)). At its lower end this cylinder has an inwardly extending ring which serves to retain a stack of fibre plates, which are clamped between the ring and the metal housing of the

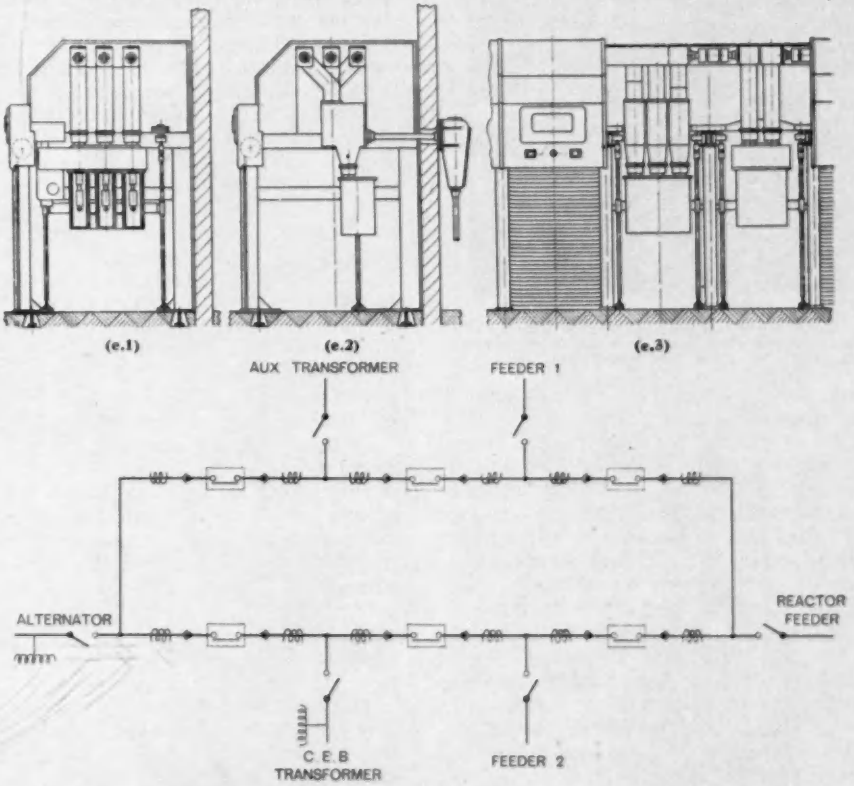


Fig. 5 (contd.)—33 kV mesh connected unit.

(e.1) Side view of circuit breaker.
(e.2) Side view of voltage transformer, isolator and cable box.
(e.3) Front view showing, from left to right, a circuit breaker, a voltage transformer and another circuit breaker.
(e.4) Schematic diagram of connections of a mesh-connected switchboard having 4 circuits

fixed contact, and are so shaped as to provide the series of cavities and lateral vents mentioned above.

So far as possible the use of external main current carrying contacts is avoided and the main current is carried by the arc contacts inside the arc control pots. This is possible up to a normal current of 800 amperes, but for heavier normal currents and for rated

Fig. 6.—Cable way behind the fire wall at the rear of a 33 kV board, showing the cable-boxes and also the operating supply 'bus wires with tee-off fuse boxes.

breaking currents above a certain value, it becomes necessary to provide external contacts. These are of the well-tried wedge and finger type giving a high pressure contact and a self-cleaning contact surface; the moving main contacts are integral with the moving contact crossbars, which consist of castings of a special copper alloy of high strength and conductivity. The moving arc contacts consist of cylindrical members formed by copper tubes or rods with removable contact tips which are faced with G.E.C. Heavy Alloy; this alloy of tungsten and copper presents an extremely high resistance to burning by the arc. If the rated breaking current is high the fixed arcing contacts may also be faced with Heavy Alloy.

The moving contacts are supported by lifting insulators consisting of plates of panilax synthetic resin bonded paper board. The guides for the moving contacts are in the form of cylindrical members moving inside fixed cylinders. The parts are so formed that they constitute effective oil dash pots which absorb the kinetic energy of the moving parts at the finish of the opening stroke, and in addition house the accelerating springs. Each moving contact is connected by links to one of the levers keyed and clamped to the main operating shaft, which in its turn is actuated by the operating mechanism.

Circuit Breaker Operating Mechanism.

A typical solenoid operating mechanism is shown in fig. 9.

The front portion of the breaker top plate is extended to form the iron circuit of the solenoid and the housing for the closing coil, a fabricated steel bracket being bolted to its underside to house the latching gear shaft and latching levers. A drive consisting of powerful toggle levers is taken from the ends of the driving shaft to the main operating shaft which is mounted inside the top plate, and carries the main lifting levers. The latch consists of multiple levers and is, of course, trip-free at any position. The tripping coils are fixed beneath the latching gear enclosure and the leads from these and from the closing coil are taken to auxiliary contacts mounted in a case fixed to the top cover. These contacts engage with others on the fixed portion of the unit when the breaker is raised to service position. Jumper connections are provided to complete the closing and tripping circuits when the breaker has been lowered so that it may be operated in the isolated position. Alternatively, flexible connections may be provided so that the breaker may be lowered without breaking the auxiliary connections.

In the spring closing mechanism, a typical example of which is shown in fig. 10, a battery of springs is compressed by a powerful toggle actuated by a worm reduction gear driven either by hand or by a motor. After being compressed, the springs may be released either by a local manual control lever or by remote electrical operation, and, in extending, close the breaker contacts. The latching and tripping mechanism is similar to that of the solenoid operating gear.

The arrangement is such that the springs may be recharged whilst the breaker is closed. It is therefore possible to reclose the breaker immediately it opens without first having to charge the springs. An interlock prevents the charged springs being released unless the breaker is in the "off" position, while a shock absorber is provided so that, should the

mechanism become unlatched when the breaker is in the "off" position and the springs are charged, the energy of the springs is absorbed without damage to the mechanism.

Manual operation is provided in all cases for use in an emergency or for contact inspection and adjustment. All breakers are fitted with full stroke tripping mechanism, the action of which is independent of the position of the contacts.

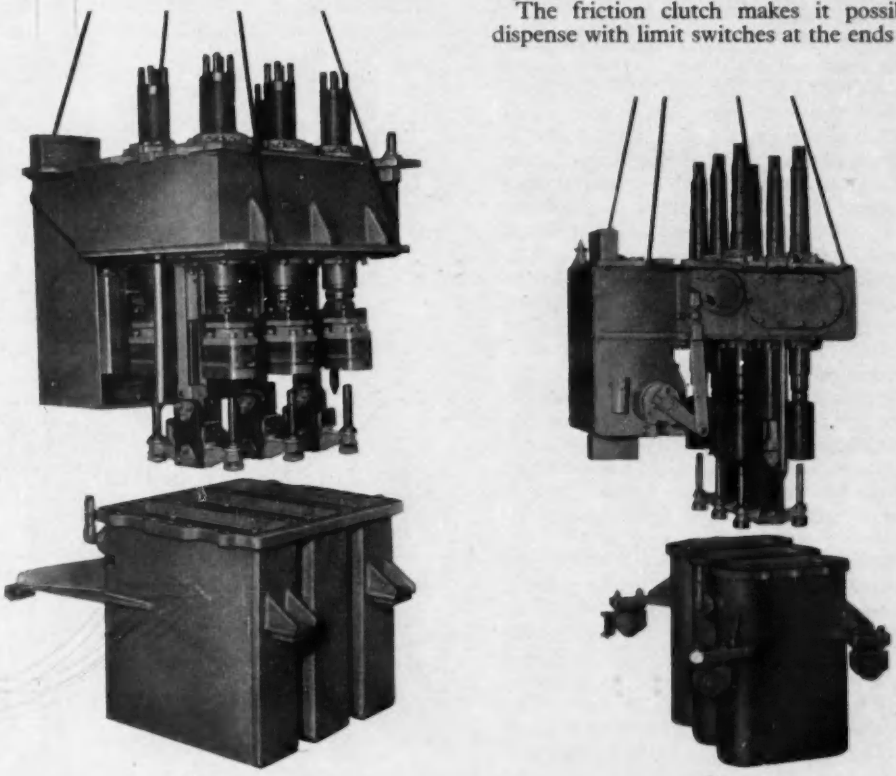
Breakers for ratings which involve very high making duties, *e.g.*, 750 MVA at 11 kV, are fitted with an electrical making trip, which trips the breaker automatically and instantaneously if it is closed upon a fault. The making trip consists of two current transformers each feeding a direct acting trip coil. A special auxiliary switch short circuits the trip coils as soon as the contacts are fully home. The trip is thus operative only during the time that the contacts are partially closed, and becomes inoperative when the breaker is fully closed.

Circuit Breaker Raising and Lowering Gear.

Each unit has a self-contained hoist gear which consists of four vertical screws hanging by universal joints from double thrust ball bearings and guided by self-lubricating journal bearings. The screws carry nuts which run up and down as the screws rotate, and these, in turn, carry steel beams upon which the breaker is supported. In the case of double bus transfer breaker units, these beams form the rails upon which the breaker is traversed from the position corresponding to the front bars to that corresponding to the rear bars.

The screws are driven by an electric motor through a friction clutch and a worm reduction gear which is connected through a chain reduction drive to one of the hoist screws. A further chain couples the four hoist screws together so that all rotate simultaneously.

The friction clutch makes it possible to dispense with limit switches at the ends of the



(a) (b)

Fig. 7.—(a) 11 kV low oil content circuit breaker, with tank removed. (b) 33 kV low oil content circuit breaker with tank removed.

(a)

(b)

Fig. 8—(a) Side blast arc control pot with fixed and moving arc contacts, and fixed main contacts for use in an 11 kV circuit breaker.
(b) Side blast arc control pot for use in 33 kV circuit breaker with fixed and moving contacts.

travel of the hoist gear. When the breaker is being plugged into the isolating contacts the motor is simply run until the breaker comes to rest, the tension on the friction clutch being adjusted so that sufficient torque is available to overcome the friction of the isolating contacts.

The guide bearings at the lower ends of the screws are arranged to lift free of the supporting base so that the hoist screws may be swung clear of the breaker when the latter is being removed from the unit.

The motor control switch is conveniently mounted just inside the roller shutter together with indicators and instructions for its use. Provision is made for attaching a hand drive which permits the breaker to be raised or lowered in the event of failure of supply to the motor.

Busbar Structure.

The whole of the busbar structure consists of a series of condenser bushings which are connected together by means of joints housed in steel joint chambers. A typical condenser bushing is shown in fig. 11, while fig. 12 shows a three phase set of connection chambers. The chambers may be filled with compound or oil or with a non-inflammable insulating medium such as Aroclor.

The connections inside the chambers are generally arranged to be flexible as shown in fig. 4, and are covered by rounded stress shields to reduce the voltage gradient in the oil or compound filling. The spout insulators are of porcelain, their upper ends being surrounded by stress shields to control the distribution of potential along their internal surfaces.

The connection chambers are fabricated from sheet steel; inserts of non-magnetic steel and non-magnetic iron castings are used where necessary to avoid complete magnetic circuits around the conductors. Some typical examples of the fabrications used in this gear are shown by fig. 13, which is a good illustration of the progress achieved in this technique.

ISOLATING CONTACTS AND AUTOMATIC SHUTTERS

Each isolating contact consists of a number of self-aligning plugs, each having a spherical end which is divided by slots into four flexible prongs; these are mounted on the top of the condenser bushings forming the terminals of the circuit breaker (fig. 14) and make contact with sockets drilled into the contact blocks supported by the busbar and feeder spout insulators.

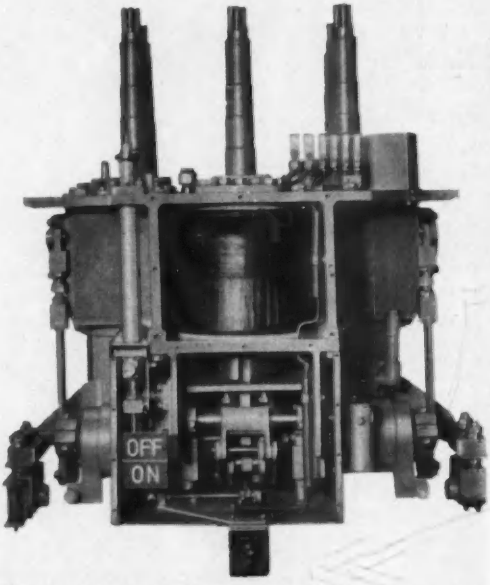


Fig. 9.—Solenoid operating gear for 33 kV oil circuit breaker

The plugs on the terminals and their corresponding sockets in the isolating spouts are jig set and positively guided into alignment by guides secured to the pedestals on both sides of the breaker.

The busbar, feeder, and voltage transformer spouts are covered automatically by shutters of the sliding plate type as the moving contacts reach their isolation positions. The levers operating these shutters are located in a central position and are thus readily accessible for locking.

Each set of shutters may be locked or opened independently of the others for the purpose of testing or earthing the busbars or cables, or for cleaning.

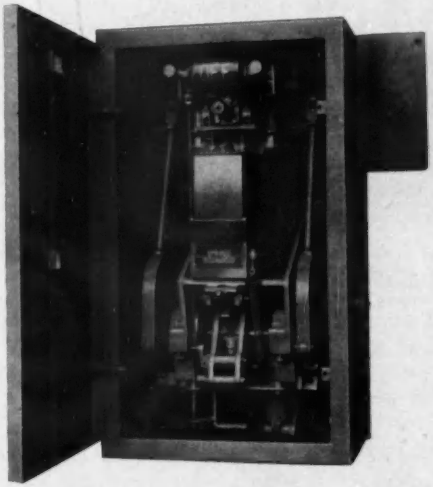


Fig. 10.—Hand-wound spring operated closing mechanism.

Current Transformers.

Ring type current transformers are used for all units; in the case of 22 kV and 33 kV installations the transformers are threaded over condenser bushings between connection boxes, so that they are accessible at any time for inspection. This arrangement effects a considerable reduction in the amount of oil or compound in the units as compared with the more usual disposition of the current transformers in oil filled chambers.

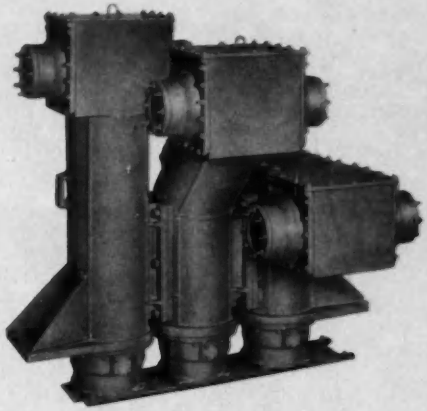


Fig. 12.—A set of tee-joint and spout insulator chambers from a 33 kV switchboard. The bushings enter the chambers by the flanges at the sides.

The mounting of the current transformers is seen from fig. 4, which shows how, by emptying the chambers on either side of the transformers, breaking the joints in the conductor and detaching the bushing flanges from the chamber walls, a bushing may be removed complete with its associated transformers, should this be required for substitution of the transformers.

The transformers are protected by a metal cover, while the secondary connections are neatly grouped and led into the main wiring trunk mentioned below (fig. 15).

In units for 11 kV the saving in oil or compound which could be effected by external mounting of the current transformers is small, and a more compact arrangement, having regard to the smaller clearances required at the lower voltage, has been achieved by accommodating the transformers in chambers in the conventional manner.

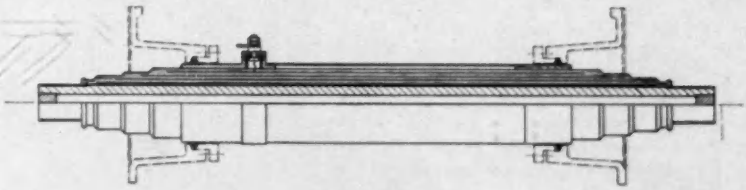


Fig. 11.—Typical 33 kV condenser bushing insulator as used for busbars and connections. The outer layer of the condenser bushing is connected to an insulated terminal which may be disconnected from earth for the purpose of dielectric tests upon the bushing.

Voltage Transformers.

As illustrated in fig. 4, voltage transformers for 22 kV and 33 kV are arranged to plug in to the connections between the current transformers and cables, by means of vertical spouts with automatic shutters similar to those for the circuit breaker.

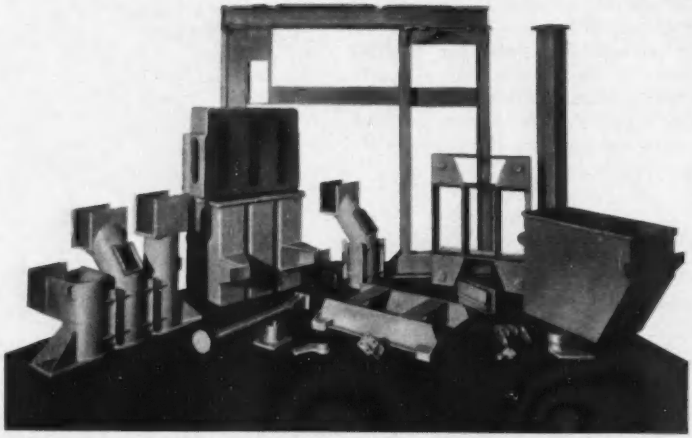


Fig. 13.—Group of typical fabricated steel parts for metalclad switchgear. The group includes, from left to right, a set of busbar tee-joint chambers, a circuit breaker top plate and tank, a busbar chamber, a complete pedestal, the front upright of a pedestal, two transport bogie bodies, a voltage transformer tank and several detail parts.

The transformer, the protective fuses and the oil tank are bolted to the underside of the top plate which carries the bushings. The lower ends of the latter project into synthetic varnish impregnated paper tubes inside which are the limiting resistances; the fuses are supported alongside the tubes. At the inside are situated the contacts by means of which the primary connections to the transformer are broken under oil when the transformer is isolated. Spring loaded rods pass through the bushings and make contact with the female contacts in the spouts. As the transformer is lowered, these rods maintain contact at their upper ends, being moved upwards in the bushings by the springs, until the oil immersed contacts have broken. On raising the transformer the reverse action takes place, the circuit being made under oil.

Access to the transformer and fuses is obtained by lowering the transformer until the top plate rests upon the supports provided for this purpose, then unbolting the tank and continuing to lower this by means of the transformer hoist mechanism, which is of the screw and chain type. Secondary fuses are mounted on the upper side of the transformer top plate in a readily accessible position. The transformer may be removed from the unit through the gangway at the rear in cases where the cables are disposed as in figs. 4, 5(a) or 5(d), or by passing it underneath the circuit breaker, in which case the bushings are first removed.

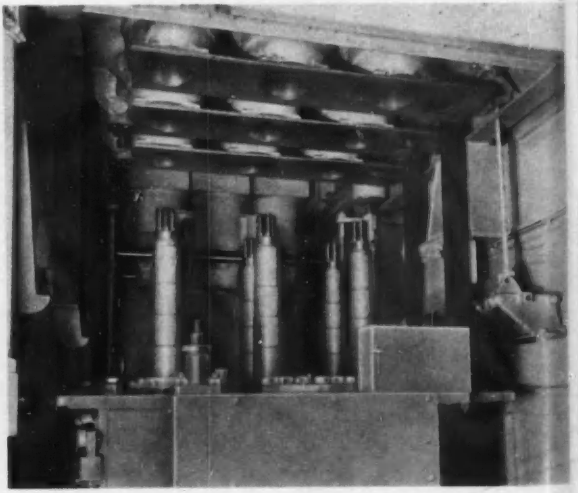


Fig. 14.—Typical circuit breaker bushing insulators, isolating contacts, busbar and feeder spouts and automatic shutters.

The voltage transformers for 11 kV units are usually situated above the current transformers and are isolated by being withdrawn horizontally; the primary fuses may then be removed, without opening up the transformer chamber, by unscrewing three caps which expose the ends of the insulating tubes which carry the fuses.

Cable Boxes.

All cable boxes are designed to be oil-tight so that oil filling may be used if desired; very ample clearances and space for making off the cones are provided. A range of boxes is available in which there is sufficient space for the use of condenser cones on the cable ends.

Ancillary Apparatus.

The solenoid contactor and non-inductive resistance, the auxiliary switches, local controller and changeover switch when required, breaker position indicator and hand trip mechanism, and, in the case of duplicate busbar units, the busbar position indicator, are mounted in a panel immediately above the roller shutter which encloses the front of the unit (fig. 16). Access is provided by a hinged door, while the indicators and hand trip button are mounted just below the door. The wiring between this panel, the current and voltage transformers and the circuit breaker is carried in troughs formed in the supporting pedestals, and may be inspected at any time by removing the covers of these troughs.

The operating supplies for the closing solenoids and hoist gear is taken from an auxiliary bus wire which may be run along a compartment in the top of the ancillary panels mentioned above. Where the cable boxes are separated from the units by a wall, it is preferable to run the 'bus wires along the far side of the wall, taking a separate connection to each unit by a conduit passing through the wall.

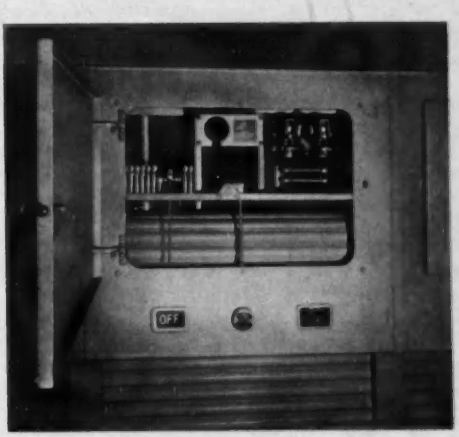


Fig. 16.—View of front panel of 11 kV unit showing auxiliary switches, indicators, closing contactor, local control switch, etc.

Interlocks and Safety Features.

A complete system of interlocking is applied in order to prevent inadvertent mal-operation of the various components. Thus it is impossible to raise the breaker into, or lower it from, the service position without first opening its contacts. Also it is impossible to raise the breaker into the service position with its tank removed, or to gain access to the voltage transformers or their fuses without first isolating them. All spout shutters are automatically operated, clearly marked, and capable of being independently locked. Permanent instruction plates are attached to the shutter gear and to the hoist mechanism control switch. Earthing gear is provided which may be attached to the circuit breaker and raised with it into the spouts, so that either a feeder or the busbars may be safely earthed.

Fig. 15.—Current transformers in a 33 kV duplicate busbar switchboard, seen from the rear upper gangway.

CONCLUSION.

The main features of the switchgear which has been described above may be summarised as follows :—

1. The use of an extremely simple, compact, double-break, low oil content circuit breaker, the contacts of which may be inspected without removing the oil from the tank or breaking oil-tight joints. The breaker may be removed bodily for maintenance or replaced by a spare breaker at any time. The breaker is isolated from the busbars by simple plugs, no oil immersed isolating switches being required.
2. Vertical isolation of the circuit breakers and consequent absence of horizontal spout insulators.
3. Maximum reduction of the amount of compound used in filling the busbar structure, by the use of condenser bushing busbars and connections.
4. The use of fabricated steel construction throughout the gear.
5. Complete phase separation.
6. Complete enclosure of each unit in dust-proof and fire-resisting steel covers with roller shutter doors.
7. Accessibility of all parts for inspection and maintenance, including the current transformer secondaries.
8. Maximum protection against fire due to the inherent reliability and simplicity of the gear, the reduction of the amount of inflammable material used and its enclosure in steel containers, and to compliance with the suggestions for avoidance of fire risk put forward by the Electricity Commissioners and H.M. Electrical Inspector of Factories.
9. Neat and serviceable appearance.

War Emergency Economies in Electrical Equipment.

In compliance with the request of the Ministry of Supply that publicity be given to their recommendations for stricter economy in the use of materials employed in the manufacture of electrical equipment, the G.E.C. are glad to publish the following notes, based on the Ministry's suggestions and amplified by examples drawn from their own experience.

THE Directorate of Industrial Electrical Equipment (Ministry of Supply) recently issued to manufacturers of electrical equipment the following memorandum on the selection and loading of industrial electric motors and control gear. At the same time the manufacturers were asked to bring these recommendations to the notice of their customers and those concerned with the specification and application of such equipment.

The situation demands that every man-hour and every pound of material are used to best advantage and to meet immediate needs. British electric motors and control gear are made to specifications which have provided ample margin and have enabled them to withstand onerous conditions in all parts of the world. This memorandum outlines certain steps by which full advantage is taken of these margins in the selection and use of motors and control gear.

1. *Selection.*

(*a*) Motors and control gear to be of the simplest mechanical and electrical

design, suitable for the immediate purpose for which they are required.

(*b*) Motors to be alternating current, squirrel cage, ventilated, single speed type wherever possible. The highest speed which will meet the conditions of the drive to be selected.

(*c*) Motors and control gear up to and including 5 b.h.p. to be arranged for direct-to-line starting wherever conditions permit.

(*d*) Control gear, other than that arranged for direct-to-line starting, to be hand operated wherever conditions of operation and safety permit.

(*e*) Control gear not to be fitted with electrical indicating instruments unless such instruments are essential to the satisfactory operation of the driven equipment.

2. *Loading.*

The following procedure to be adopted when purchasing or specifying open, protected or ventilated, continuously rated A.C. and D.C. motors up to and including 500 b.h.p. at any speed, whenever such motors are for normal use in Great Britain or in countries where similar ambient temperatures apply.

(*a*) The required duty to be assessed accurately. Wherever possible the actual horse power and torque necessary for the drive should be determined by test. Full regard to be paid to intermittent load conditions.

(*b*) The horse power rating in accordance with the appropriate British Standard Specification to be that which is at least 90 per cent of that required to meet the duty assessed as at (*a*).

(*c*) The control gear rating to be based on the rated British Standard Specification horse power of the motor as determined at (*b*).

Example.

The required horse power as determined under (*a*) is 33. 90 per cent of 33 equals 29·7.

Specify a standard 30 h.p. motor to British Standard Specification No. 168 with control gear rated for 30 b.h.p.

It should not be necessary to stress the importance of this memorandum to engineers to-day or to dwell upon the reasons that have made the utmost economy in the use of man hours and materials so vital in the war effort, but some amplifications of this statement may help in carrying out the recommendations. In the first place it may be mentioned that in copper alone the electrical industry consumes some 50 per cent of the total usage of this metal in this country. It is not in copper alone, however, that economy is necessary; all metals and materials employed in engineering to-day are precious, but in electrical engineering a saving in copper automatically effects savings in other materials. One of the principal sources of waste springs from the conservative British practice of providing a small extra margin in order to be on the safe side. The cumulative effect of this practice can obviously become inordinately large if, in estimating the power and plant required in a complete scheme, safety margins are added at several stages. It should be remembered that power factor falls off rapidly at partial loads and especially so with smaller motors, so that it is of prime importance that such machines should, so far as possible, always operate at or near full load. For these reasons the memorandum and the advertising campaign now being conducted in the technical press lay emphasis on the importance of using the smaller motor for the bigger job, and on the elimination of safety margins.

In order for manufacturers to assist as fully as possible, it is very necessary for them to consider the whole problem of economy in the use of materials from the general aspect, and not merely as a question of using smaller motors. Associated equipment, such as switchgear, cables, generating plant and transformers are equally important. It is also necessary to revise entirely for the period of war the traditional outlook on safety margins and the length of life of any piece of plant. Higher temperature rises and shortened life are to be expected, but even though the life of a motor or transformer may be reduced from 30 to 5 years, to take an extreme case, it will have achieved its object if it has saved, and therefore made available for munitions, valuable materials and thus have helped in winning the war.

As a practical step in this direction, all engineers who are responsible for specifying

or installing electrical equipment should be thoroughly familiar with the revised cable ratings issued by the Institution of Electrical Engineers and the War Emergency Specifications for generators, transformers, etc., of the British Standards Institution.

The new British Standard War Emergency Specification No. 1084, which applies to generators to be driven by internal combustion engines, is a glaring instance of the wasteful indulgence of our peace-time methods. How futile it has been to provide electrical plant with a 25 per cent overload margin on its rated capacity and to couple such plant to driving units such as internal combustion engines which only possess a 10 per cent margin of overload capacity.

These specifications represent the effort made by designers and users of electrical equipment to provide safe and economical standards for electrical gear for war purposes. It is not necessary to allow extra margins or provide safety factors beyond this. But savings made in the design of equipment can represent only a small part of the possible effective saving, as it is so much a matter for users of electrical equipment and those recommending and specifying new plant to do so on the lines of the recommendations that have been made. A great deal of plant is still being installed for conditions of service that are entirely new and for which previous similar experience cannot be available. It is difficult in such circumstances to avoid the unwanted increase in safety margins and sometimes, again, to avoid specifying equipment not of standard design. Full co-operation between the manufacturer and the user here is the only possible solution. The importance of avoiding the use of non-standard equipment cannot be over emphasised. Every engineer will appreciate the bad effect on production when interruptions have to be made to manufacture special equipment.

As a practical example, typical of the way in which economies can be effected very simply, the following may be worth recording. A standard line of machines produced in large quantities formerly carried brass nameplates on which were recorded the usual particulars as to size and rating. These nameplates were superseded by a card treated with a coat of protective varnish and secured in a light metal holder mounted on the frame of the machine. In the aggregate the quantity of metal regularly saved by this simple substitution is quite considerable.

For plant already installed, the possibilities of making savings are not so great but motors which are known to be operating at a low load and power factor should be changed when the opportunity offers to use them more efficiently elsewhere, as, for instance, when a scheme of re-arrangement or extension is taking place. Numerous instances, however, will occur to engineers operating industrial electrical equipment of ways in which considerable savings can be made. The need is urgent, and the end will surely justify the means.